npj | heritage science

Article

https://doi.org/10.1038/s40494-025-01877-7

Cultural gene characterization and mapping of traditional tibetan village landscapes in Western Sichuan, China

Check for updates

Ding Fan [1,2] ✉, Nor Zarifah Binti Maliki [2], Chuan He [1] ✉, Yu Bi [1] ✉ & Siwei Yu [1]

This study employs cultural landscape gene theory to deconstruct traditional village landscapes into five key gene units and examines their interactions through field surveys, GIS mapping, and multivariate analysis (PCA and AHP). Four gene types are identified: primary, additional, mixed, and variant. Each type fulfills distinct roles: primary genes (e.g., religious beliefs) define the core cultural identity; additional genes (architectural and artistic elements) reinforce spatial and structural stability; mixed genes (linguistic and festive traditions) reflect adaptive intercultural blending; and variant genes (e.g., evolving settlement patterns) respond to socio-environmental dynamics. The synergistic functioning of these genes contributes to the resilience and continuity of cultural landscapes. This research proposes a systematic framework for interpreting the complexity of ethnic heritage spaces. It provides theoretical insights and empirical references for sustainable ethno-rural planning and preserving cultural identity and diversity.

Traditional Tibetan villages in western Sichuan are renowned for their distinct cultural landscapes, integral to China's diverse ethnic mosaic[1]. These villages epitomize the Tibetan ethos of harmony with nature and embody profound cultural and ethnic significance[2,3]. Recognized for their unique cultural attributes, these areas are invaluable treasures of global cultural heritage[4]. However, rapid urbanization and globalization threaten their traditional lifestyles, architectural uniqueness, and cultural integrity[5]. Although scholars have investigated the sustainability of these cultural landscapes, existing research predominantly focuses on isolated cultural or geographic elements, lacking a systematic approach to examining multi-cultural landscape characteristics and conducting regional comparisons[6,7]. Despite their affiliation with different Tibetan tribes, these villages share common characteristics in their cultural landscapes while preserving distinct ethnic and cultural attributes. This interplay between shared features and local variations is central to understanding the coexistence of cultural diversity and unity within the Tibetan landscape. The similarities reflect shared historical and environmental influences, whereas the differences safeguard the unique identities of each tribe, enriching Tibetan culture. To address these gaps, this study investigates villages from different Tibetan tribes in western Sichuan, integrating Geographic Information Systems (GIS) with cultural landscape gene theory. This approach establishes a comprehensive framework for analyzing and preserving these landscapes, highlighting the interplay between spatial and cultural dimensions while elucidating the structural and functional aspects of cultural landscape genes[8–10]. The findings enhance understanding of Tibetan cultural characteristics and patterns, illustrating how shared and distinct features collectively contribute to the resilience and diversity of these landscapes. The study proposes innovative strategies for heritage conservation and provides valuable references for preserving the cultural landscapes of minority regions worldwide, especially amid modernization and environmental challenges.

The concept of a cultural landscape encapsulates the intricate interplay between cultural practices, beliefs, and the surrounding environment. It extends beyond physical elements to encompass intangible cultural factors, including traditions, religious practices, and social behaviors within a spatial context. In contrast to "culture" or "landscape," which are frequently examined independently, a cultural landscape synthesizes these dimensions to illustrate how communities shape, utilize, and perceive their environment. This integrated perspective underpins the theoretical foundation of cultural landscape gene theory, which deconstructs landscapes into their smallest, most stable, and adaptive components to facilitate systematic study and conservation[9,11].

Tibetan villages in western Sichuan are vital to China's rich tapestry of ethnic minority cultures, embodying a cultural landscape abundant in tangible and intangible dimensions. This landscape encompasses the geographical setting, traditional architecture, folk festivals, religious beliefs, and ethnic arts[2]. The concept of cultural landscape genes, drawing inspiration from genetics, offers a structured framework for analyzing these elements,

[1]School of Art and Design, Le Shan Normal University, Sichuan Province, China. [2]School of Housing, Building and Planning, Universiti Sains Malaysia, Penang, Malaysia. ✉e-mail: fanding@student.usm.my; hc12221@163.com; biyu753951@icloud.com

identifying their core components and interrelations that shape village cultures[11]. These "genes" represent the smallest stable units of the cultural landscape, and their preservation is critical to sustaining the authenticity and diversity of Tibetan village cultures.

Recent studies have increasingly emphasized identifying and analyzing the components of traditional village cultural landscapes, with a particular focus on conservation and sustainable development[12–14]. Methodologies such as hierarchical analysis, fuzzy comprehensive evaluation, and Geographic Information Systems (GIS) have played a pivotal role in developing structured models to assess the interplay between natural and cultural resources. These models, rooted in cultural landscape gene theory, have demonstrated their significance in mapping and analyzing the fundamental components of cultural landscapes, facilitating their adaptation to environmental changes and modernization pressures[15–17].

However, most studies have examined individual landscape components in isolation, often focusing on specific cultural elements, such as architecture or rituals, while overlooking the interconnectedness of these elements[16,18,19]. For instance, Fan et al. (2023) applied fractal theory to investigate the formation mechanisms of Tibetan villages, providing novel insights into cultural heritage preservation[2]. Nevertheless, the study primarily focuses on structural patterns, potentially neglecting the dynamic cultural practices that bring vitality to these spaces. Similarly, Wei (2019) integrated landscape gene theory and historical analysis to examine the relationship between architectural landscapes and settlement environments in Tibetan and Qiang villages, revealing how these relationships evolve in response to environmental and social changes[20]. Nonetheless, this approach is constrained in its ability to capture the complexity of cultural interactions and the diverse influences that shape these landscapes.

While previous studies have made valuable contributions[21–23], a significant gap remains in comparative analyses of Tibetan tribal villages. Such analyses could illuminate the territorial and systemic characteristics of these landscapes. This study addresses these gaps by systematically applying cultural landscape gene theory to compare the cultural landscapes of eight nationally recognized Tibetan villages representing five distinct tribes[24,25]. Incorporating methodologies such as gene identification, encoding, classification, and comparison[26–29], this research aims to uncover the intricate interactions among regional landscape features, ethnic cultural networks, and structural elements, thereby proposing a novel framework for understanding and conserving Tibetan cultural heritage[30].

This comprehensive approach not only addresses the limitations identified in prior studies but also contributes to the discourse on preserving cultural landscapes in ethnic minority regions[23], providing valuable insights into the challenges and opportunities faced by these communities amid modernization pressures[31–33]. Future research could build upon these findings by applying similar frameworks to other ethnic regions, further investigating the dynamic interplay between cultural heritage and modernity.

Methods

Overview of the study area

The Tibetan villages selected for this study are located in western Sichuan Province, including the Garzê Tibetan Autonomous Prefecture, the Ngawa Tibetan and Qiang Autonomous Prefecture, Pingwu County (Mianyang City), and Shimian County (Ya'an City), as shown in Fig. 1. These sites were selected for their cultural characteristics, historical significance, and roles in local societies, as detailed in the *Catalog of Traditional Chinese Villages*. The study examines eight representative Tibetan traditional villages: Che Ma Village and Re La Village (Kham Tibetans), Xi Suo Village and Song Gang Village (Jiarong Tibetans), Shen Zuo Village (Amdo Tibetans), Min Zu Village and Er Li Village (Baima Tibetans), and Jiang Ba Village (Ersu Tibetans). Located in high-altitude mountainous regions, these villages feature distinctive architectural styles and rich natural and cultural resources[34,35]. Over the past decade, implementing the rural revitalization

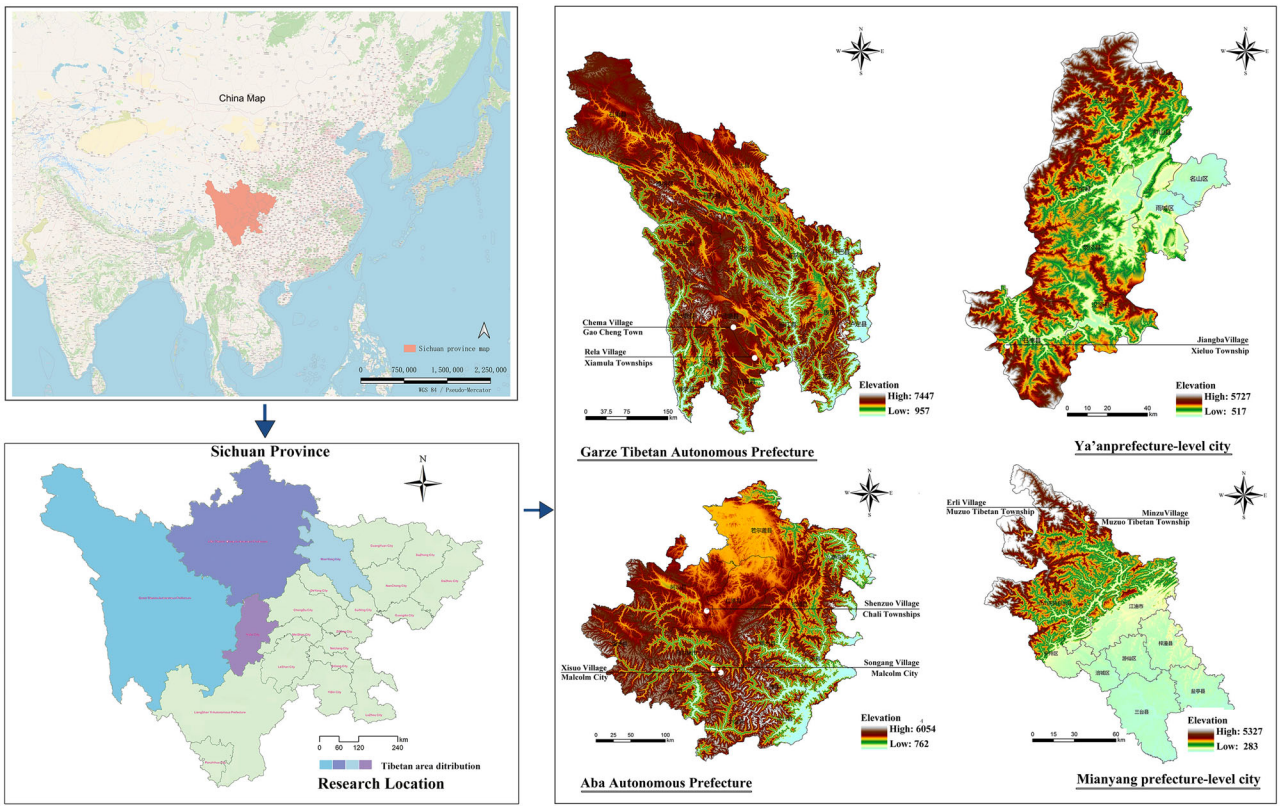


Fig. 1 | Research area. (Fig. 1 was created using ArcMap 10.8, QGIS 3.22.5. The base map in Fig. 1 is sourced from OpenStreetMap contributors and used under the Open Database License (ODbL), available at https://www.openstreetmap.org/copyright).

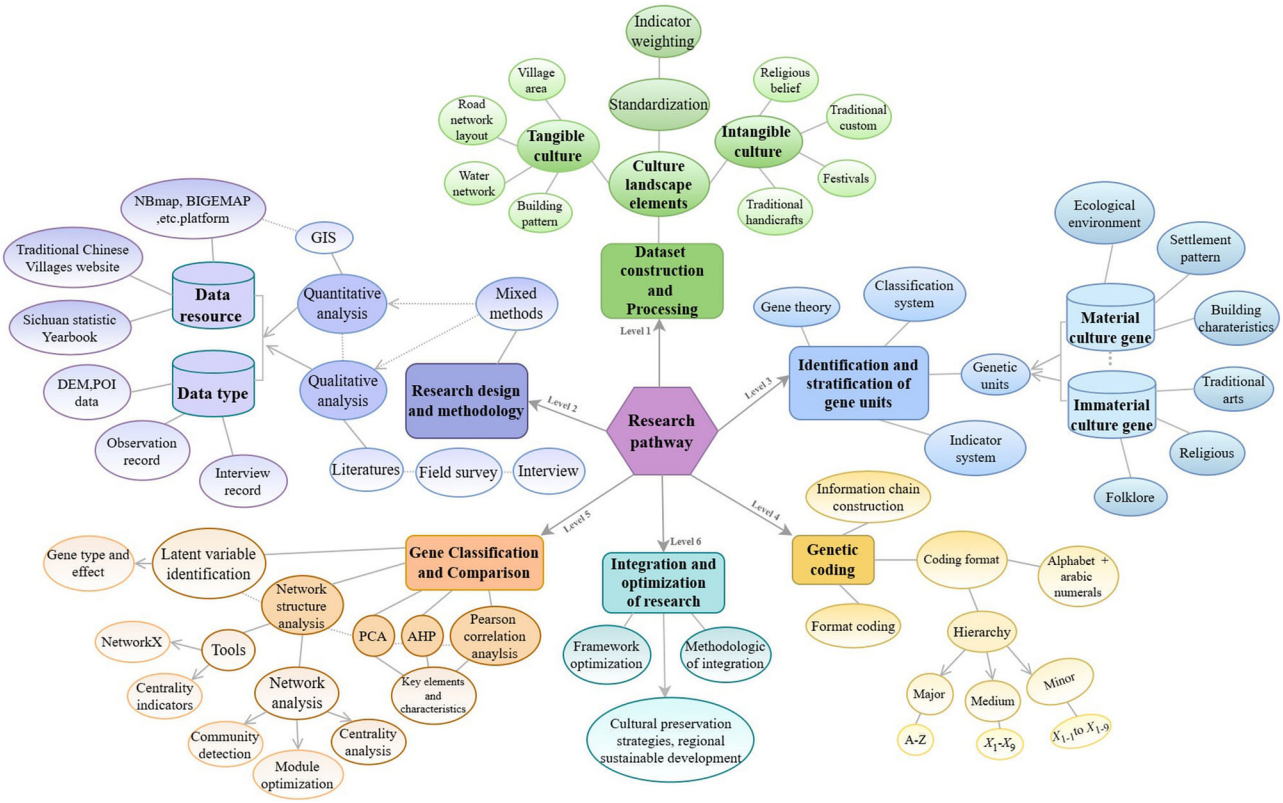


Fig. 2 | Research process flowchart.

strategy has significantly improved the ecological environment and social development in these Tibetan villages.

Research approach

The flowchart (Fig. 2) illustrates the research framework employed in this study, which integrates multiple methods to analyze the cultural landscapes of Tibetan villages systematically. The following sections provide a detailed explanation of each step in the framework.

Data resource and type

This study adopts a mixed-methods approach, integrating quantitative and qualitative analyses to examine the cultural landscapes of traditional Tibetan villages[1,36].

The quantitative analysis primarily utilizes Geographic Information Systems (GIS) with data from GIS Cloud and Map Open Platform, including 30-meter resolution Digital Elevation Models (DEM) and Points of Interest (POI) data. Additional data sourced from the Traditional Chinese Villages website and the Sichuan Statistical Yearbook website quantify the villages' geographic locations, topographical environments, settlement patterns, facility distributions, spatial usage, and foundational sociocultural information. Qualitative data collected through in-depth interviews, observations, and literature reviews complement the quantitative data by offering insights into the sociocultural dynamics underlying the numbers, providing essential information for constructing the dataset[37].

Interviews were conducted from January to December 2022, ensuring comprehensive data collection across seasons and enabling the study to capture potential temporal variations in cultural practices. For qualitative interviews, 24 participants were selected using purposive sampling to ensure representation across community roles, including village elders, cultural practitioners, and local leaders. The criteria for participant selection included: (1) residency in the village for over 10 years, (2) active participation in cultural practices, and (3) knowledge of local traditions. This sampling strategy ensured comprehensive data collection, capturing diverse cultural perspectives while allowing for cross-village comparisons. Informed consent was obtained from all participants, and their identities were anonymized for confidentiality[38,39]. Interviews lasted between 32 and 110 minutes and were conducted via online video calls or in-person group discussions, depending on participants' availability and preferences[40]. This approach enabled a dynamic exploration of topics, including family tradition transmission, local festival characteristics, and the impact of modern rural development on traditional culture.

All interview sessions were audio-recorded with participants' consent and transcribed for subsequent textual analysis. Data anonymization measures included removing identifiable details and assigning unique identifiers to each dataset (see Table 1). The qualitative data analysis software NVivo was used to facilitate content analysis. Recorded content was systematically coded to identify themes, including community cultural transmission, policy impact, and the interaction between cultural resources and village development[41].

To reduce interviewer bias and minimize the effects of cultural differences that could distort data interpretation, a culturally diverse team of researchers conducted the interviews[42]. The team regularly reviewed and discussed findings to challenge and refine thematic interpretations. They also revisited key interview segments to ensure balanced data representation and understanding.

Although the interviews yielded valuable insights, they inherently have limitations, as the perspectives are specific to certain groups and do not represent all relevant communities[43]. The interviewer's potential subjectivity could influence question framing and interpretation. Additionally, cultural differences between researchers and respondents may result in misunderstandings[44,45]. To address these challenges, we integrated survey data with literature sources to enhance the study's comprehensiveness and supplement quantitative data and observational findings.

Table 1 | Thematic classification and coding

Topic category	Encodings	Description	Key topic words	Frequency
Traditional Culture and Values	TCV	Exploration of traditional family and community values and their transmission to the next generation.	TCV-01: Family Traditions TCV-02: Community Values TCV-03: Cultural Norms	L M M
Community Development and The Impact of Modernization	CDIM	Analysis of the impact of modernization on traditional culture, including external factors such as education and technology.	CDIM-01: Urbanization Effects CDIM-02: Technological Impact CDIM-03: Economic Changes	M M L
Cultural Diversity and Integration	CDI	Examination of cultural diversity and the interaction of different cultural backgrounds within the community.	CDI-01: Ethnic Minorities CDI-02: Multicultural Interaction CDI-03: Integration Policies	MH M L
Religion and Cultural Practices	RCP	Exploration of the role of religion, festivals, and rituals in shaping community culture.	RCP-01: Religious Beliefs RCP-02: Spiritual Rituals RCP-03: Cultural Celebrations	H MH H
Cultural Heritage Preservation and Policy	CHPPI	Analysis of government roles in heritage preservation and community challenges.	CHPPI-01: Heritage Sites CHPPI-02: Conservation Laws CHPPI-03: Government Involvement	H M M
Community Integration and Cultural Activity	CICA	Description of how cultural activities enhance community cohesion and youth participation.	CICA-01: Social Cohesion CICA-02: Cultural Festivals CICA-03: Community Arts	M H MH
Cultural Roots and History	CRH	Exploration of folklore, oral history, and cultural identity in transmission.	CRH-01: Historical Landmarks CRH-02: Ancestral Practices CRH-03: Historical Narratives	L M M
Religious Architecture and Cultural Contributions	RACC	Examination of monasteries, houses, and handicrafts in cultural heritage.	RACC-01: Sacred Buildings RACC-02: Architectural Styles RACC-03: Cultural Landmarks	H L M

(Themes and keywords were systematically extracted from interview data to comprehensively address the research questions. *Frequency* indicates the occurrence rate of each theme in the interviews, categorized as *High* (H), *Moderately High* (MH), *Medium* (M), and *Low* (L) based on the frequency of relevant keywords).

Dataset construction and processing

The dataset for this study is constructed through a systematic analysis of both material and immaterial cultural landscape elements. Field surveys, interviews, and literature reviews were conducted to extract 17 variables, capturing and quantifying the cultural landscape characteristics of the villages.

The collected data comprises eight material cultural landscape elements, including village area, road network layout, water system distribution, architectural patterns, and others[46]. These elements are numerically processed using standardized measures and ratios to enable analysis in subsequent statistical models. The remaining nine immaterial cultural landscape elements, such as religious beliefs, traditional customs, and festival activities, are compiled from literature reviews and interview data to construct the dataset[47]. Most of these data are text-based qualitative data, which require encoding strategies to transform them into quantitative indicators for statistical analysis; that is, different weights and values are assigned based on the impact level of each immaterial cultural element. We use the StandardScaler from the Sklearn Python preprocessing module, which standardizes features by mean removal and unit variance scaling. This normalization ensures that data of varying scales are compared using a consistent standard. This process improves data operability and analytical precision, providing a solid foundation for subsequent complex analyses and model construction, as shown in Table 2 below.

Identification and stratification of genetic units

To systematically analyze the data and uncover the cultural landscape genes of Tibetan villages, we applied a gene theory framework previously used by other researchers[22,48,49]. This approach allows us to identify groups with similar characteristics within complex datasets and pinpoint the cultural landscape gene units to which each element belongs. We identified two types of genes in traditional Tibetan villages: material cultural landscape genes and immaterial cultural landscape genes[16,17,50]. To facilitate this, we constructed an index system with analytical units such as settlement patterns, architectural features, religious beliefs, and traditional crafts. These indicators encompass multidimensional cultural elements, ranging from village-scale features to festival activities. This structured approach systematically categorizes and clarifies the various components of the cultural landscape of Tibetan villages, providing a comprehensive framework for analysis and conservation efforts (as shown in Table 3). The indicator system proposed in this study serves as a foundational framework for systematically characterizing cultural landscapes. While the indicators are tailored to reflect the interplay between cultural and spatial dimensions, they also allow for adaptation and refinement in future research to accommodate localized or dynamic cultural features.

Gene encoding

After defining the structure of landscape elements and units, we applied gene theory to encode these elements. This process aims to precisely identify and delineate the key components of the traditional Tibetan village cultural landscapes in Western Sichuan. By converting complex cultural characteristics into quantifiable data, we can more effectively systematize the analysis and understanding of the structure and features of cultural landscapes[51]. This method helps distill the core elements of the cultural landscape, revealing the distinctive features of Tibetan cultural landscapes and providing clear indicators for their preservation and transmission.

Table 2 | Data set of cultural landscape elements in sample villages

Villages	VA	RNP	WSP	BP	BT	BF	BFu	BD	DC	TAF	TC	RS	RB	TW	LT	TF	LC
Chema	−1.13	−1.51	−1.00	−1.12	−0.77	−1.32	−0.77	−0.77	−1.26	−1.51	−0.77	−0.77	−0.77	−1.51	−0.77	−1.29	−0.77
Rela	−1.13	−0.30	−1.00	1.44	−0.77	−1.32	−0.77	−0.77	−1.26	−1.51	−0.77	−0.77	−0.77	−1.51	−0.77	−1.29	−0.77
Songgang	0.38	0.90	1.00	0.16	−0.77	−0.76	−0.77	−0.77	−0.54	−0.30	−0.77	−0.77	−0.77	−0.30	−0.77	−0.26	−0.77
Xisuo	−1.13	−1.51	1.00	0.16	−0.77	−0.21	−0.77	−0.77	−0.54	−0.30	−0.77	−0.77	−0.77	−0.30	−0.77	−0.26	−0.77
Shenzuo	0.38	0.90	−1.00	−1.12	−0.77	0.35	−0.77	−0.77	0.18	0.90	−0.77	−0.77	−0.77	0.90	−0.77	−0.26	−0.77
Minzu	0.38	0.90	1.00	0.16	1.29	0.90	1.29	1.29	0.90	0.90	1.29	1.29	1.29	0.90	1.29	0.77	1.29
Erli	0.38	0.90	−1.00	−1.12	1.29	0.90	1.29	1.29	0.90	0.90	1.29	1.29	1.29	0.90	1.29	0.77	1.29
Jiangba	1.89	−0.30	1.00	1.44	1.29	1.46	1.29	1.29	1.62	0.90	1.29	1.29	1.29	0.90	1.29	1.81	1.29

VA Village Area (Km^2), *RNP* Road Network Pattern, *WSP* Water System Pattern, *BL* Building Pattern, *BT* Building Type, *BF* Building Form, *BFu* Building Function, *BD* Building Decorate, *DC* Dress Characteristics, *TAF* Traditional Art Form, *TC* Traditional Crafts, *RS* Religious Sect, *RB* Religious Belief, *TW* Totem Worship, *LT* Language and Text, *TF* Traditional Festival, *LC* Liturgical Customs.

In biology, bases are arranged in specific sequences to form DNA, which constitutes essential materials and coenzymes of life, carrying rich genetic information[52]. Similarly, in our research, the elements of rural cultural landscapes are regarded as "bases," combined in various sequences to form landscape gene units, producing diverse cultural landscape phenomena and rural characteristics. Following the principle of like-with-like merging, we applied existing information categorization and encoding techniques to encode the cultural landscape genes of five Tibetan tribal villages. According to the landscape gene encoding model[53], the codes are represented using the "English initial + Arabic numeral format." The coding includes three levels: significant categories (represented by the letters A-Z), middle categories (represented by numbers 1–9), such as x_1, and subcategories (ranging from 1–1 to 1–9), such as $x_{(1-1)}$, constructing a chain of village cultural landscape gene information (as shown in Fig. 3).

This systematic coding process allows us to effectively organize and analyze cultural landscape data, contributing to a deeper understanding of the unique cultural elements and their interactions in Tibetan villages.

Gene classification and comparison

This section employs a combination of Pearson correlation, Principal Component Analysis (PCA), and the Analytical Hierarchy Process (AHP) to examine latent variables and their roles within the cultural landscape of traditional Tibetan villages in Western Sichuan[54,55]. The aim is to use these methods to identify the fundamental types and impacts of cultural genes and the similarities and differences between the cultural landscapes of different villages[56]. These methods facilitate understanding the diversity and continuity of cultural elements across various village cultures. Additionally, the insights gained are invaluable for formulating strategies for cultural revitalization and protection and promoting regional economic and social development.

Firstly, correlation analysis explores the specific relationships between these identified elements. This method allows us to quantify the strength and direction of relationships between elements, allowing us to explain their direct correlations or indirect influences. The formula for calculating Pearson correlation is as follows:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^{(y_i - \bar{y})}}} \quad (1)$$

Where, x_i and y_i represent the observed values while $\bar{x}$ and $\bar{y}$ are their respective means. The symbol r denotes the Pearson correlation coefficient, which measures the strength and direction of the linear relationship between two quantitative variables. The r value ranges from -1 to 1, where 1 indicates a perfect positive correlation, -1 indicates a perfect negative correlation, and 0 indicates no linear correlation. Correlation analysis is a fundamental tool for examining relationships among variables. It is used to test linear relationships among elements[57], providing insights into how different variables interact.

Second, Principal Component Analysis (PCA) is a dimensionality reduction technique used to effectively extract and summarize key variables in data, uncovering underlying structures or patterns[58]. Calculating eigenvalues and loadings is a critical step in PCA. A high eigenvalue indicates significant variation in data along that direction, suggesting that it contains substantial information and holds considerable importance in the dataset. The magnitude of loadings reflects the contribution of original variables to the principal component, representing their importance in forming the principal component[59]. The equation for PCA involves the following steps:

$$|C - \lambda I| = 0 \quad (2)$$

Where C is the covariance matrix, λ is the eigenvalue, and I is the unit matrix. The eigenvalues are the values corresponding to the eigenvectors of

Table 3 | Indicator system for genetic characterization of cultural landscapes

Landscape genotypes	Factor layer	Indicator layer	Indicator analysis
Material Culture Landscape Gene	Spatial pattern	Village scale	Size, boundary, historical evolution, etc.
		Building layout	Distribution, densities, form, symbolic significance, etc.
		Road layout	Road network structure
		Water system layout	Area, distribution, cultural and symbolic functions, etc.
	Architecture landscape	Building layout	Distribution, densities, form,
		Building style	Residential buildings, Temple
		Building form	Proportions, styles, materials, symbolic representation, etc.
		Building function	Living, production, religious, etc.
		Building decoration	Construction techniques, patterns, symbolic meanings, etc.
Immaterial Culture Landscape Gene	Traditional art	Costume feature	Accessories, clothing styles, regional cultural significance, etc.
		Art performance	Painting, calligraphy, sculpture, song, dance, opera, spatial setting, etc.
		Traditional handcrafts	Furniture, embroidery, knitting, etc.
	Religious beliefs	Religious sect	Gelugpa, Nyingma, Benjaminism, etc.
		Totem worship	Natural objects, gods, figures, etc.
		Religious customs	Chanting, Debating, Gatherings, associated spatial features, etc.
	Folk custom	Language and Text	Dialect, Tibetan text, etc.
		Traditional festival	Tibetan New Year, Sun Buddha Festival, mountain worship festival, spatial impact, etc.
		Etiquette habits	Marriage, Funeral, Respect for Teachers, spatial manifestation, etc.

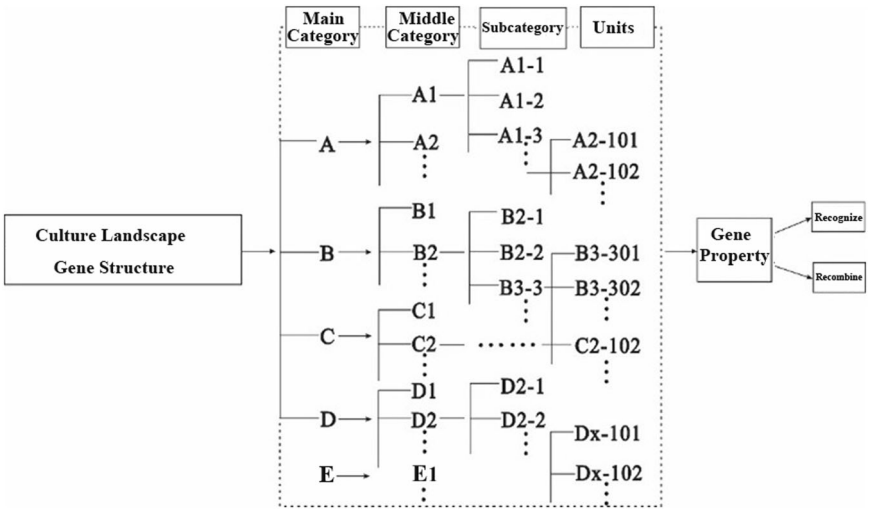


Fig. 3 | Cultural gene coding model.

the covariance matrix, which this equation can obtain.

$$Load_{ij} = \sqrt{\lambda_j} \times v_{ij} \tag{3}$$

where λ_j is the jth eigenvalue and v_{ij} is the ith element of the jth eigenvector. The loadings are critical to explain the actual meaning of each principal component.

Subsequently, the Analytic Hierarchy Process (AHP) is applied to evaluate the weights of various landscape elements, enabling precise definition of gene types. AHP is a multi-criteria decision-making tool that tackles complex issues by conducting pairwise comparisons of elements across levels, ranking LINGcategorizing extracted elements, and assigning weights to systematically evaluate the relative importance of each cultural landscape gene[60]. This method enables a more precise understanding and interpretation of the multidimensional characteristics of cultural landscapes in traditional Tibetan villages of western Sichuan[61]. The weight distribution basis is formulated based on the structure of the cultural landscape gene characteristic index system established in the previous section (Table 4) and integrates information from consultations with folklore scholars and field surveys. Next, a rating matrix A is constructed to quantify the relative importance of various factors. Each pair of factors is assigned a scale value from 1 to 9, reflecting their relative importance[62]. Then, compute the weight vector $W = (w_1, w_2, w_3, \ldots w_n)$, obtained by normalizing the eigenvectors corresponding to the largest eigenvalues of the judgment matrix A with the expression:

$$AW = \lambda_{max} W \tag{4}$$

where A is the judgment matrix, W is the weight vector, and λ_{max} is the maximum eigenvalue of A.

To ensure the rationality of the assessment process, we further perform a consistency test on the judgment matrix. The consistency index (CI) and

Table 4 | Clustering and coding information of cultural landscape genes

Landscape Gene	♦ **Material Cultural Landscape Gene** ♦ **Immaterial Cultural Landscape Gene**
Major Category	**A** Spatial Pattern Gene, **B** Building Characteristics Gene, **C** Traditional Art Gene, **D** Religious Belief Gene, **E** Culture Folk
Middle Category	♦ **A1** Village Size, **A2** Road Network Layout, **A3** Water System Layout, **A4** Building Pattern ♦ **B1** Building Type, **B2** Building Form, **B3** Building Function, **B4** Building Decoration ♦ **C1** Dress Characteristics, **C2** Traditional Crafts, **C3** Traditional Art Form ♦ **D1** Religious Sect, **D2** Religious Custom, **D3** Totemic Worship ♦ **E1** Language and Text, **E2** Traditional Festival, **E3** Liturgical Customs
Subcategory	♦ **A1-1** Village boundary, **A1-2** Topographical, **A1-3** Scale,**A2-1** Shape,**A2-2** Surface material,**A3-1** Form,**A3-2** Area,**A4-1** Scale,**A4-2** Form,**A4-3** Location ♦ **B1-1** Traditional dwelling, **B1-2** Temple building, **B2-1** Plane pattern, **B2-2** Roof style, **B2-3** Material, **B3-1** Living or production, ♦ **B4-1** Color, **B4-2** Patterns and motifs, **B4-3** Form of expression. ♦ **C1-1** Baldric, **C1-2** Material/Color, **C2-1** School, **C2-2** Content, **C3-1** ♦ **D1-1, D2-1, D2-2, D3-1, D3-2** ♦ **E1-1** Language Family, **E1-2** Dialect, **E1-3** Text, **E2-1, E3-1**
Unit components	♦ **A1-101** Nature environment; **A1-102** History events. **A1-201** High Mountain type; **A1-202** Middle Mountain type; **A1-203** Low Mountain type; **A1-204** Location and orientation **A1-301** Land using and type; **A1-302** Household and a permanent population ♦ **A2-101** Fishbone shape; **A2-102** Branch shape; **A2-103** Z-shape; **A2-104** Row and column shape **A2-201** Cement Road; **A2-202** Slate Road; **A2-203** Mud Road ♦ **A3-101** Irregularly; **A3-102** Dependent on terrain **A3-201** Number and distribution; **A3-202** Water body type; **A3-203** Climate change ♦ **A4-101** High altitude; **A4-102** Resident land use. **A4-201** Aggregation type; **A4-202** Dispersion type; **A4-203** Aggregation and Dispersion type; **A4-204** Irregular type; **A4-301** Waterfront type; **A4-302** Dependent on mountainous terrain ♦ **B1-101** Flat type; **B1-102** Dry column type; **B1-201** Buddhist temple; **B1-202** Tibetan scripture pavilion; **B1-203** Monk residence; **B1-204** Stupa; **B1-205** Annex building. ♦ **B2-101** "Enclosed"shape; **B2-102**"String"shape; **B2-103**"Dented"shape; **B2-104** Convex shape; **B2-105** Three-sided or Four-sided courtyard; **B2-106** Square; **B2-107** Rectangle; **B2-108** Trapezoid.**B2-201** Flat roof; **B2-202** Shed roof, **B2-202** Gable and Hip roof; **B2-203** Fudian roof, **B2-301** Stone; **B2-302** Rammed earth; **B2-303** Flaky; **B2-304** Clay; **B2-305** Blue Tile, ♦ **B3-101** Living, drying, party activities; **B3-102** Poultry breeding. ♦ **B4-201** Buddha's lights bottle pattern; **B4-202** Babao Ji Xiang pattern; **B4-203** Treasure flower pattern; **B4-204** Sanskrit pattern. ; **B4-301** Carvings; **B4-302** Drawing. ♦ **C1-101** Clothing style; **C1-102** Belt; **C1-103** Headdress; **C1-201** Clothing material; **C1-202** Accessories material; **C1-203** Color matching. ♦ **C2-101** Gazi sect; **C2-102** Qinze sect; **C2-103** Miantang sect; **C2-201** Buddhist stories.**C2-202** Myths and Legends; **C2-203** National Epic ♦ **C3-101** Song, **C3-102** Dance, **C3-103**-Opera ♦ **D1-101** Gelu sect; **D1-102** Nyingma sect; **D1-103** Sakya sect; **D1-104** Yongzhongben sect ♦ **D2-101** Worship, Chanting and Praying.**D2-201:** Put up a banner. ♦ **D3-101** Rock; **D3-102** Sun and moon; **D3-103** Grains; **D3-104** Rams; **D3-105** Cows; **D3-106** Ancestors ; **D3-201** Folklore; **D3-202** History inheritance ♦ **E1-101** Kangba Language; **E1-102** Jajong Language; **E1-103** Ando Language.**E1-104** Baima Language; **E1-105** Ersu Language.**E1-201** Font style; **E1-202** Graphic symbol. ♦ **E2-101** Tibetan New Year; Sai Buddha festival; Mountain worshiping festival; Archery festival, etc. ♦ **E3-101** Marriages and funerals, respect for new Buddhist teaching, respect for elders and monks

(The hierarchical categorization approach of this table begins with major categories that represent broad cultural and spatial dimensions, followed by subcategories and unit components that define specific characteristics. While the system focuses on the most important components, it also serves as a foundational framework that provides flexibility for refinement and expansion for future research.)

consistency ratio (*CR*) are calculated as follows:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{5}$$

$$\mathrm{CR} = \frac{CI}{RI} \tag{6}$$

where $\lambda_{\max}$ is the maximum eigenvalue of the judgment matrix, n is the dimension or order of the judgment matrix, and RI is the random consistency index. The consistency of the judgment matrix is considered acceptable only if the value of CR is less than 0.1. This step of consistency testing ensured that our judgments in assessing the relative importance of different cultural landscape factors were robust and credible[60].

Additionally, network structure analysis was employed to examine the commonalities and differences in cultural landscape genes. This method analyzes complex interactions among elements from a macro perspective, revealing structural patterns that establish cultural connections and highlight the uniqueness of each gene characteristic across different villages[63,64]. In this analysis, a network of cultural landscape elements is constructed by defining nodes (i.e., cultural elements) and edges (i.e., connections between components). Centrality analysis evaluates the importance of a node within the network using two key metrics: Degree Centrality, which measures the number of connections a node has, and Betweenness Centrality, which reflects how often a node serves as a bridge along the shortest path between other nodes. The equation is as follows:

$$C_D(i) = \frac{deg(i)}{\mathrm{N} - 1} \tag{7}$$

Here, $C_D(i)$ is the degree centrality of node i, $deg(i)$ is the degree of node i (i.e., the number of direct connections), and N is the total number of nodes in the network.

$$C_B(i) = \sum_{j<k} \frac{gjk(i)}{gjk} \tag{8}$$

Here, $C_B(i)$ is the median centrality of node i, gjk is the number of shortest paths from node j to node k, and $gjk(i)$ is the number of paths that pass through i among these paths.

We applied community detection algorithms to reveal clusters in the network that represent villages with similar cultural traits. Methods such as modularity optimization were used to evaluate the density of connections within communities, refining the group structures of artistic elements and highlighting their commonalities and differences. This process employs the NetworkX module in Python[65].

The integration of the methods has improved the accuracy of classifying the cultural landscape genes of Tibetan villages and enhanced the understanding of their cultural diversity, continuity, and differences. These methods streamline the data processing workflow and establish a systematic and scientific analytical framework. This framework offers robust theoretical and methodological support for dissecting and comprehensively assessing cultural landscape genes and formulating conservation strategies.

Results

Characterization of the genetic units of the cultural landscape

Tibetan villages on the western Sichuan Plateau present a distinctive cultural landscape integrating elements from Han, Yi, Qiang, and Miao ethnic groups. This fusion is reflected in local architecture, art, and traditions, arising from prolonged interaction and adaptation between the community and its environment. These interactions underscore the dynamic processes of cultural gene inheritance, variation, and selection, showcasing cultural diversity and resilience[53,66]. This section examines the material and immaterial "gene units" of these villages, focusing on spatial patterns, architectural styles, traditional crafts, religious customs, language, and festival traditions. This study aims to extract and analyze these gene units through case studies, revealing their distinctive roles within the cultural landscape[67,68]. This approach underscores the vitality and resilience of cultural integration, highlighting the complex processes by which these cultural elements are preserved and transformed.

Spatial pattern gene unit

The spatial layout of Tibetan villages on the western Sichuan Plateau is predominantly influenced by topography, road networks, and architectural styles[1]. Typically situated in high-altitude areas, these villages blend seamlessly into the surrounding local rivers, woodlands, and grasslands. This integration reflects a long-standing symbiosis between humans and nature, highlighting the region's complex and diverse environmental landscape[2]. Village streets and alleys, which form the backbone of the village structure, connect residential zones with public spaces, enhancing connectivity and accessibility. Figure 4a illustrates this, showing that Che Ma Village and Xi Suo Village have dense building and population clusters influenced by their road layouts. In contrast, Re La Village and Jiang Ba Village align their road layouts with natural water systems, reflecting minimal impact on the terrain. Similarly, Shen Zuo Village and Erli Village exhibit minimal terrain influence on their road designs. By contrast, Song Gang Village and Min Zu Village feature winding roads adapted to hilly landscapes[69]. These variations underscore the unique adaptations of Tibetan villages to their geographic settings, highlighting their role in shaping the cultural landscape. This is illustrated by field-photographed settlement patterns, using Xisuo, Jiangba, and Shenzuo as examples (see Fig. 4b).

Architectural landscape gene unit

Tibetan village architecture is primarily divided into residential houses and temples. It is influenced by local terrain, road networks, and water systems, resulting in complex and diverse spatial layouts[70,71]. Residential structures are typically "broadly dispersed yet closely grouped in small clusters". Architecturally, Khampa, Jiarong, and Amdo Tibetans favor towered houses, ranging from simple square forms to complex polygons. In contrast, the Ershu and Baima Tibetans typically adopt Sichuan's architectural layout's "enclosed" design. Common building materials, such as rammed earth, slate, and raw timber, are used with varying construction techniques. Roofs are flat, sloped, or hipped, incorporating traditional and modern elements (see Fig. 4c). The typical Tibetan home layout comprises a ground floor for livestock, a second floor for living, and a third floor serving as a prayer hall, reflecting the spiritual hierarchy of gods, humans, and animals. This architecture meets practical needs for living, worship, and animal husbandry while reflecting the esthetic values and social structures of different tribes, highlighting the historical and cultural evolution of these ethnic groups.

Temple architecture plays a central role in Tibetan villages, shaped by Buddhist doctrines and ethnic culture. Temples are typically constructed at higher elevations, often centered around mountains, reflecting the Mandala-inspired Buddhist cosmology and the concept of the three realms[72]. These temples serve as centers for religious activities and are integral to the community's cultural life. For instance, temples such as Litang Monastery, Manzhou Monastery, Changlie Monastery, and Danda Lun Monastery are either located next to or surrounding villages or adopt a "temple above, village below" layout (see Fig. 4d). The spatial positioning of temples in Tibetan villages underscores their integration with both daily life and the natural landscape[73].

Typically located at elevated sites near mountains, these temples embody Mandala-inspired cosmology and the concept of the three realms, symbolizing harmony between humans, spirituality, and nature. This strategic placement underscores the community's deep reverence for religious culture and emphasizes temple architecture as a focal point for both spiritual and social life[72]. Prominent examples, such as the Litang, Manzhou, Changlie, and Danda Lun Monasteries, are often arranged in a "temple above, village below" configuration (Fig. 4d), overlooking or surrounding the villages. This layout seamlessly integrates religious practices with daily life, reflecting the community's profound respect for nature and spirituality while reinforcing the temples' role as centers of cultural cohesion[73].

Among the Khampa, Jiarong, and Amdo tribes, Buddhist temples exhibit distinctive architectural styles, categorized as Tibetan flat-roofed and Sino-Tibetan hybrid designs (see Fig. 4e). These structures are meticulously constructed with traditional materials, including stone, wood, earth, and brick concrete, prioritizing durability and esthetic harmony. Key architectural components include the main Buddha Hall, scripture halls, monks' quarters, stupas, and auxiliary buildings. Additionally, decorations vary and feature traditional Buddhist motifs, including the "Buddha Light Vase" and "Eight Auspicious Symbols"[11,62,74]. These elements are designed to accommodate religious practices and community gatherings.

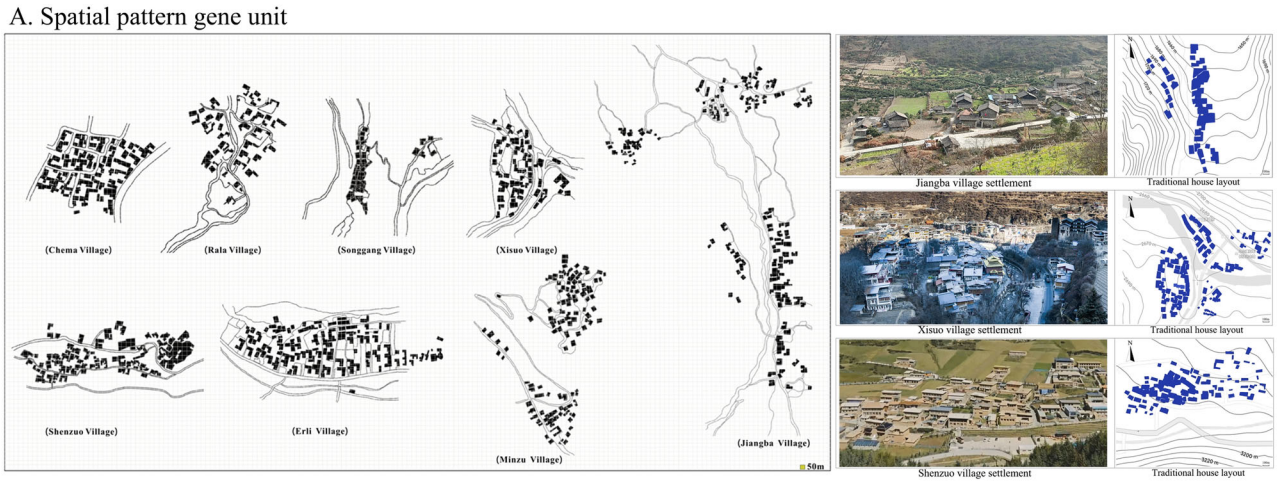
In villages such as Erli and Minzu (among the Baima Tibetans) and Jiangba (among the Ersu Tibetans), where the Bon religion is predominant, natural elements are venerated as incarnations of spirits. Consequently, these villages lack prominent Buddhist temples and instead feature smaller, widely distributed shrines, such as mountain god temples and land god temples, situated along mountainsides or within fields and courtyards[75,76]. These settings illustrate the integration of residential and religious spaces, highlighting the unified relationship among spirit, culture, and nature within Tibetan villages.

Traditional art gene unit

Tibetan art forms on the western Sichuan Plateau are integral to the cultural landscape, reflecting a rich tapestry of heritage and customs across tribes and highlighting the unique fusion of multi-ethnic integration[77]. These art forms encompass a diverse range of practices, including dyeing, weaving, calligraphy, music, dance, and metal casting. Thangka painting is particularly renowned for its intricate craftsmanship and profound religious and mythological themes[78,79]. These paintings portray religious activities and traditional life scenes, embodying intertribal beliefs and artistic expressions. According to Sanlang Ruo'erwu, a Thangka inheritor from Xi Suo Village, Thangka is both an art form and a crucial component of Tibetan intangible cultural heritage, preserving historical and religious narratives.

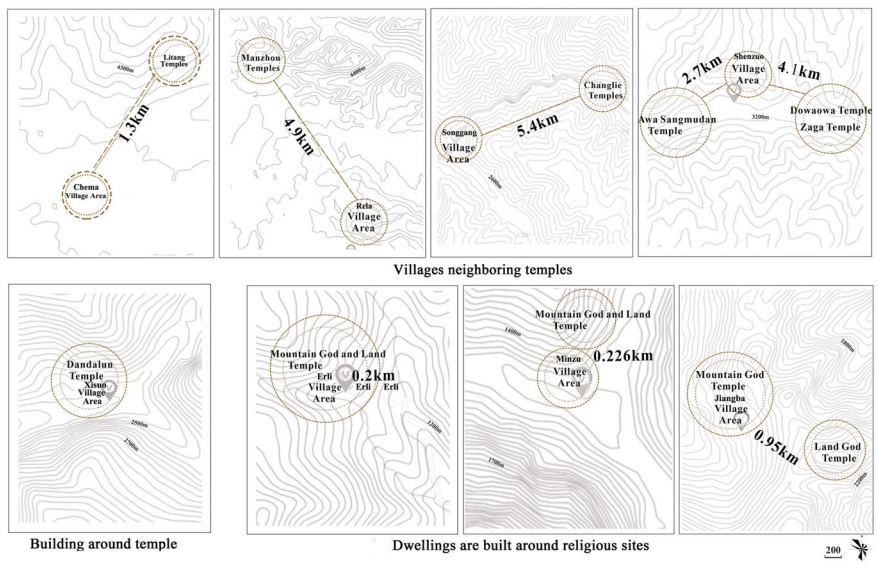
Tibetan clothing is designed for the high-altitude climate and reflects the unique traits of each tribe through distinctive styles and decorations. For example, Khampa and Amdo Tibetans wear loose robes adorned with heavy gemstones, reflecting their regional esthetic. In contrast, Jiarong and Ersu Tibetans incorporate tailoring techniques and embroidery from Qiang and Han cultures. Baima Tibetans uniquely adorn their hats with white rooster feathers, symbolizing spiritual protection. These garments are practical for daily use and reinforce tribal identity and esthetic preferences.

Tibetan utensils, furniture, and handicrafts are frequently adorned with auspicious symbols, including the Buddha Light Vase and the Eight Auspicious Symbols[80]. These designs transcend mere embellishment; they enrich daily life and convey the profound layers of Tibetan cultural expression.

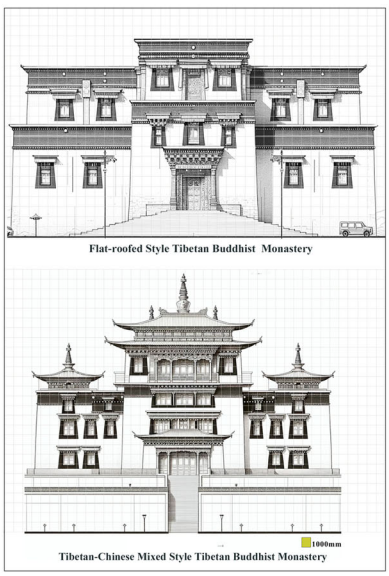


(a) Spatial pattern of village buildings and roads(self-illustration) (b) Sample village settlements (self-timer)

(c) Tibetan residential architecture of different forms and materials (Field collection)



(d) Spatial Location Characteristics of Temples (self-illustration)



(e) The temple building elevation (self-illustration)

Fig. 4 | Information on spatial patterns and architectural landscape. **a** Spatial pattern of village buildings and roads(self-illustration); **b** Sample village settlements(self-timer); **c** Tibetan residential architecture of different forms and materials(Field collection); **d** Spatial Location Characteristics of Temples(self-illustration); **e** The temple building elevation(self-illustration). (The author took photographs in this collection during a field trip. All images are original).

Religious beliefs gene unit

In Tibetan rural areas, religious beliefs form the foundation of village culture, profoundly influencing architecture, art, and daily life[81]. Temples serve as centers for religious activities and key venues for cultural heritage and community interaction[82]. The dominant Tibetan Buddhist sects in the Khampa, Jiarong, and Amdo regions are Gelug and Nyingma, whose doctrines significantly influence villages' spatial organization and public life patterns[83].

The religious belief gene in Tibetan culture is characterized by a diverse array of totemic patterns, including Buddhist deities, natural elements, and

Fig. 5 | Interview with villagers and folklorists of Crab Snail Fortress, Jiangba Village (Collected on 22nd January,2022).

Fig. 6 | Interview with Minzu Village Folklorist (Collected on 12th December, 2022). (These photos were captured during the field research interviews).

heroic figures, which symbolize the culture and reflect the fusion of religious and folk traditions[78,84]. These totems are prominently integrated into the architectural designs and interior layouts of temples, embodying the spiritual essence of religious beliefs and providing a lasting visual representation of faith[85].

Furthermore, various religious ceremonies and festivals vividly showcase the diversity of religious cultures and their pivotal role in sustaining community cultural identity. These events strengthen community bonds and act as vital links between the past and present, as well as tradition and modernity.

Folk culture gene unit

The folk culture of Tibetan regions in western Sichuan is vividly expressed through language, script, festivals, and rituals. The Tibetan language, including dialects such as Kham, Amdo, and Jiarong, is pivotal in enriching the region's cultural tapestry[86]. The principal Buddhist scriptures, the *Kangyur* and *Tengyur*, document over three thousand years of Tibetan cultural history and are written in distinctive Tibetan scripts, Kham and Ume, both of which are recognized as national intangible cultural heritage[87].

Field interviews in Minzu Village and Jiangba Village revealed that, despite lacking a formal written language, the Baima and Ersu Tibetans sustain their cultural heritage through oral traditions and artistic expressions, including songs, dances, and paintings (as illustrated in Figs. 5, 6).

Tibetan festivals and folk activities, such as the Buddha Sunning Festival, Tibetan New Year, Mountain Worship Festival, and Archery Festival, underscore the cultural and religious distinctiveness of the tribes while serving as vital conduits for cultural preservation, reflecting the deep-rooted values and history of the Tibetan people[88]. These diverse aspects of folk culture are crucial for understanding the cultural dynamics and diversity in Tibetan villages of western Sichuan[89]. They further highlight the significance of these artistic forms in fostering community cohesion, identity, and continuity[90].

Cultural landscape genetic coding and classification

Building on a previously established index system and gene information chain structure[18,28], along with gene unit characteristics and a coding structure concept(as presented in Table 3 and Fig. 3), we have classified cultural landscape genes into five major categories, 17 subcategories, 33 minor categories, and 98 landscape unit components, as detailed in Table 4.

This classification employs a top-down hierarchical framework, beginning with major categories that encompass broad cultural and spatial dimensions, including spatial patterns, architectural features, traditional arts, religious beliefs, and cultural practices. These categories were selected for their representativeness, stability, and relevance to the cultural landscape of Tibetan villages[17,48]. Subcategories and unit components were further refined to improve specificity and establish a solid foundation for comprehensive analysis.

The system emphasizes the most significant and representative components, serving as a foundational framework for systematically studying cultural landscapes. It does not exclude the potential influence of other cultural elements but prioritizes key components for systematic study. This framework can be refined and expanded in future research to include additional elements as necessary, accommodating new insights and evolving cultural contexts. (Fig. 7)

As shown in Fig. 8, Principal Component Analysis (PCA) and clustering algorithms were applied to reduce the dimensionality of mixed data, extract critical cultural landscape gene variables, and group them based on their intrinsic relationships. PCA simplified the data structure, revealed underlying patterns, and explained most of the variation through a few principal components[59]. Subsequently, cluster analysis categorized the gene units based on the similarity of these components, as depicted in Fig. 8, clarifying the types of cultural landscape gene units. The densely clustered groups in the figure indicate the presence of primary genes with shared core characteristics[91]. Gene units on the periphery indicate the presence of mixed genes, while those outside the primary clusters may represent new landscape elements shaped by external socio-economic factors.

This analysis identified four types of cultural landscape genes: central, attachment, mixed, and variant. Primary genes are fundamental, defining the main characteristics of the cultural landscape, such as architectural styles, religious beliefs, and traditional arts, which play a crucial role in shaping the cultural landscape of Tibetan villages[92]. Attachment genes

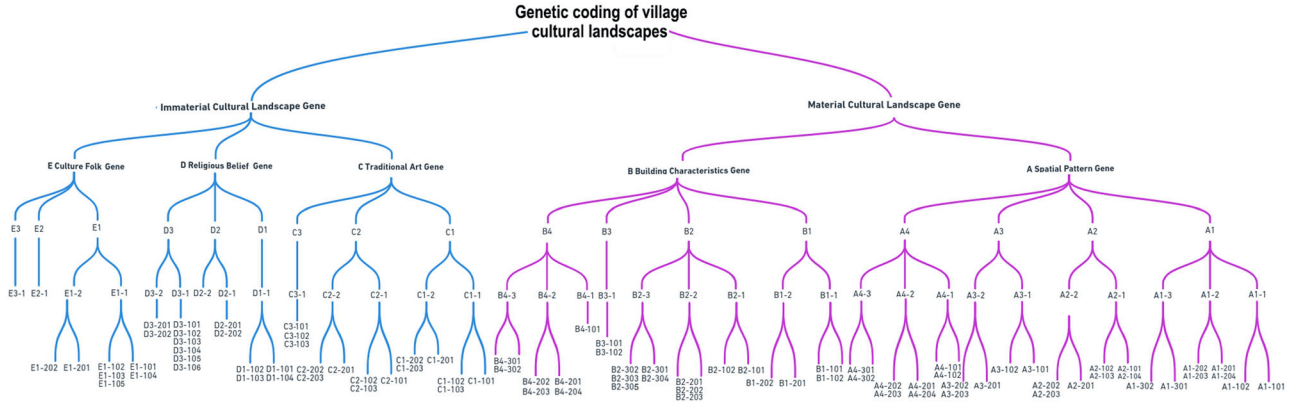
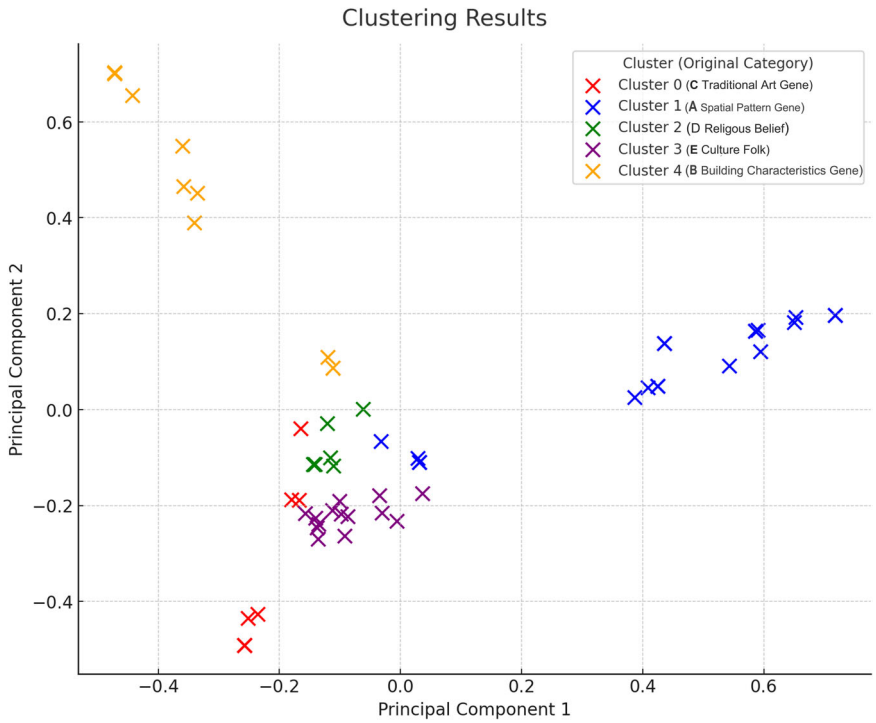


Fig. 7 | Clustering of cultural landscape gene units. (Fig. 7 illustrates the hierarchical clustering of the cultural landscape's material and immaterial elements into various groups, reflecting the gene coding structure depicted in Fig. 3. This structure demonstrates how core characteristics of cultural genes are represented and vary across different artistic expressions.).

Fig. 8 | Clustering of gene components after principal component (PCA) based dimensionality reduction.



enhance core genes by adding features or depth. Mixed genes represent the blending and interaction of different artistic elements, while variant genes reflect the introduction of new cultural elements, potentially driven by external socio-economic changes[93].

Genotypes of cultural landscape elements

This section employs correlation analysis, Principal Component Analysis (PCA), and the Analytical Hierarchy Process (AHP) to examine the five cultural landscape gene units in Tibetan villages of western Sichuan. The objective is to classify and understand the impact of these gene types on the cultural characteristics and identity of the villages. This analysis provides a scientific basis for the cultural preservation and development strategies of these villages.

Initially, the Pearson correlation coefficient (based on Eq. (1)) was applied to explore linear correlations among various cultural variables, which were visualized through a correlation matrix and a heatmap in Fig. 9. This foundational step identifies clusters of gene types and examines their significance within the cultural landscape[94], revealing how these elements interact and shape the overall cultural framework of the villages.

As shown in Fig. 9, the heatmaps illustrate the relationships between different cultural landscape gene variables, as measured by Pearson correlation coefficients. These variables are grouped into five categories: spatial patterns, architectural features, traditional arts, religious beliefs, and cultural customs. In the spatial pattern group (Fig. 9a), village size shows a positive correlation with road layout and a negative one with building arrangement. Architectural features (Fig. 9b) and cultural customs (Fig. 9e) exhibit strong intra-group correlations, reflecting internal coherence. Religious and artistic variables (Figs. 9c, d) also display notable associations, suggesting deep cultural linkages. Figure 9f integrates all five categories, illustrating a complex network of both positive and negative intergroup relationships.

To investigate the statistical structure of the cultural gene variables and reduce dimensionality, we applied principal component analysis (PCA)[62,95]. PCA transforms the original correlated variables into a set of uncorrelated principal components that collectively retain as much variance as possible

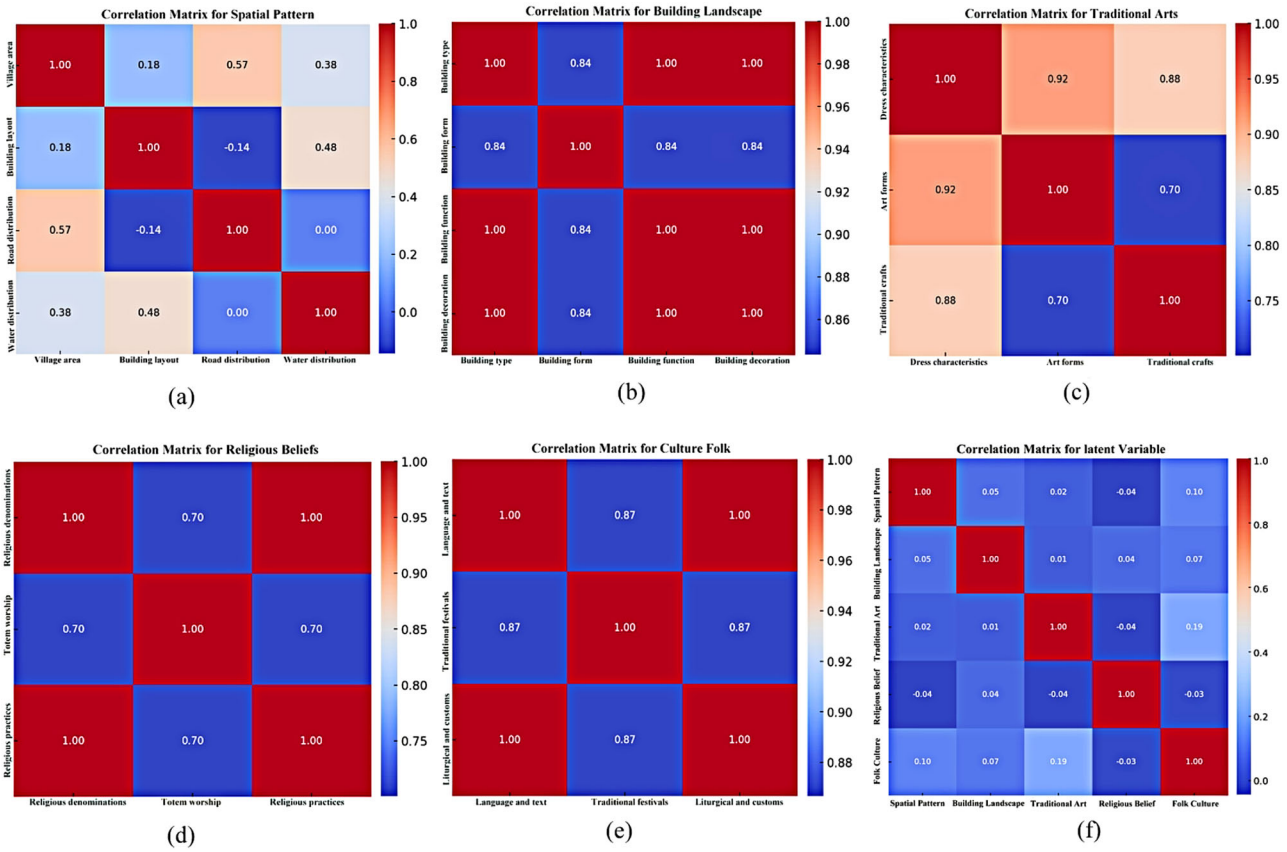


Fig. 9 | Heat map of correlation matrix between variables in gene units. **a** Correlation Matrix for Spatial Pattern; **b** Correlation Matrix for Building Landscape; **c** Correlation Matrix for Traditional Arts; **d** Correlation Matrix for Religious Belifes; **e** Correlation Matrix for Culture Folk; **f** Correlation Matrix for latent Variable.

from the dataset[96]. Each element is associated with an eigenvalue, representing the amount of variance it explains; the larger the eigenvalue, the more significant the component's contribution[97].

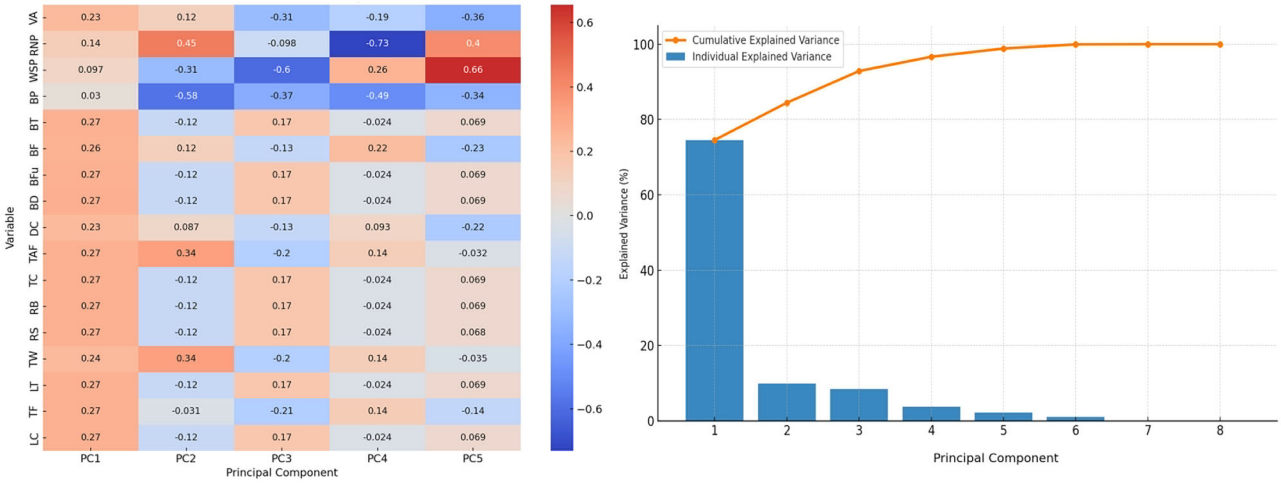
Two indicators are central to interpreting the PCA results: the loadings matrix and the explained variance. The loadings matrix quantifies the contribution of each original variable to each principal component, with higher absolute values indicating stronger associations[98]. Identifying the component with the highest loading for a given variable allows for a preliminary grouping of variables. Explained variance, meanwhile, denotes how much of the dataset's total variance each component accounts for, as calculated using Eqs. 2 and 3[99]. Components with higher explained variance highlight the principal axes of variation. Together, these indicators clarify the underlying structure and support the classification of variables based on shared statistical features.

As shown in Fig. 10, the statistical structure of landscape variables is revealed through principal component analysis (PCA). In Figure (a), the heatmap presents the loading coefficients of each variable on the first five principal components (PC1-PC5). In Figure (b), the scree plot quantifies the individual and cumulative variances explained by each principal component, highlighting the primary position of PC1.

PC1 accounts for 74.51% of the total variance, indicating its centrality in encapsulating the shared structural essence of core cultural elements. Variables related to "Religious beliefs and Religious sects" exhibit strong positive loadings on PC1, corroborating their foundational status within the cultural system. PC2 explains 7.56% of the variance and centers on architectural and functional elements (e.g., building typologies, forms, functions, and ornamentations), embodying relatively stable cultural attributes, thus justifying its preliminary classification as an Attachment Gene. PC3 (5.16% variance explained) and PC4 (3.28%) highlight dynamic, transitional cultural patterns (e.g., traditional art forms, water system configurations, and linguistic practices), reflecting intercultural interaction and adaptive flexibility, which is why they are designated as Mixed Genes. PC5 explains only 1.44% of the variance. It involves elements such as "traditional crafts, totemic worship, and festive" practices, embodying emergent or variant characteristics, which warrant its tentative classification as a Variant Gene. Components beyond PC5 yield negligible variance and lack interpretive clarity, justifying their exclusion from further analysis.

Although PCA can objectively reveal the statistical structure of variables and the primary sources of variation, as a purely data-driven method, it may not accurately reflect the importance of each variable in terms of cultural values[100]. Some variables may contribute minimally to statistical variance yet possess high cultural value. To address this gap, we supplemented the PCA with an expert-based evaluation using the Analytic Hierarchy Process (AHP). This method incorporates subjective judgment into a structured decision-making framework[101]. AHP facilitates the integration of qualitative insights with quantitative analysis by constructing a pairwise comparison matrix, allowing for the assignment of weights based on expert assessment[12]. This approach enables the inclusion of culturally meaningful but less statistically prominent variables, offering a more holistic evaluation.

Accordingly, we developed an AHP framework encompassing three evaluation dimensions. Experts were invited to assign weights to each dimension based on their knowledge and experience. The dimensions include: (1) Cultural functionality, which refers to the role of variables in cultural inheritance and functional performance, reflecting their significance and value as cultural elements[102]; (2) Adaptability, which refers to the ability of variables to adjust and inherit in response to changes in the environment and times, demonstrating their strength in maintaining existence and influence in different contexts[103]; (3) Statistical relevance, which



(a) PCA Loading Heatmap(PC1-PC5) (b) Explained variance by principal components

Fig. 10 | PCA results. a PCA loading heatmap(PC1–PC5); **b** Explained variance byprincipal components.

Table 5 | Combined factor analysis and weighting of genotypes

Principal component	The proportion of variance explained	Variable	Gene category (Initially)	Weight	Gene category (Finally)
N/A	0	Village Size	Variant Gene	0.0642	Variant Gene
PC4	3.28%	Road Network Layout	Mixed Gene	0.0690	Attachment Gene
PC3	5.16%	Water System Layout	Mixed Gene	0.0712	Attachment Gene
PC3	5.15%	Building Pattern	Mixed Gene	0.0522	Mixed Gene
PC2	7.56%	Building Type	Attachment Gene	0.0660	Attachment Gene
PC2	7.56%	Building Form	Attachment Gene	0.0596	Attachment Gene
PC2	7.56%	Building Function	Attachment Gene	0.0600	Attachment Gene
PC2	7.56%	Building Decoration	Attachment Gene	0.0669	Attachment Gene
PC2	7.56%	Dress Characteristics	Attachment Gene	0.0658	Attachment Gene
PC3	5.15%	Traditional Art Form	Mixed Gene	0.0654	Attachment Gene
PC5	1.44%	Traditional Crafts	Attachment Gene	0.0619	Attachment Gene
PC1	74.51%	Religious Belief	Main Gene	0.0618	Main Gene
PC1	74.51%	Religious Sect	Attachment Gene	0.0574	Attachment Gene
N/A	0	Liturgical Customs	Variant Gene	0.0631	Variant Gene
PC5	1.44%	Totem Worship	Variant Gene	0.0566	Variant Gene
PC4	3.28%	Language and Text	Attachment Gene	0.0588	Mixed Gene
PC5	1.44%	Traditional Festivals	Mixed Gene	0.0642	Mixed Gene

(Initial categories based on PCA Loading and variance (Fig. 10 a, b); Consistency testing confirmed the reliability of AHP judgments (CR = 0.083, CI = 0.093, RI = 1.12), confirming that the expert evaluations are logically consistent and statistically acceptable).

refers to the degree of importance of variables in statistical analysis, such as their performance in PCA, including the variance contribution and loading levels of the corresponding principal components[104].

Following the evaluation framework mentioned above, we conducted a weighted summary of the expert scores for each variable across three dimensions (cultural functionality, adaptability, and statistical relevance), ultimately obtaining a comprehensive weight for each variable (based on Eqs. 5–6). Experts independently rated all variables on a scale of 1–9, and the AHP method was used to calculate the overall scores, reflecting the importance of each variable in terms of the integrity, continuity, and adaptability of the cultural landscape system. As shown in Table 5, "water system layout" (0.0712), "road network layout" (0.0690), and "architectural decoration" (0.0669) received relatively high weights, indicating that their cultural value is more prominent in the comprehensive assessment across the three dimensions.

Based on the principal components and the weights of their variables, we determine and classify the types of effects of various cultural gene variables[97,100], as shown in Fig. 11. Variables that exhibit high loadings on a single principal component and rank highly in expert evaluation are considered Main genes. These variables contribute substantially to cultural characteristics, statistically reflecting a dominant factor, significant variance explanation, and strong functional or symbolic relevance. Conversely, variables with more evenly distributed loadings across multiple components, implying influence from several latent factors, and lower expert-assigned weights are categorized as Mixed genes. These typically serve as supportive or transitional elements within the broader cultural system.

From above, we conducted an integrated classification of cultural gene types for each variable, as presented in Table 5 and Fig. 12. For instance, religious belief and religious sect are both associated with the first principal component (PC1), which accounts for 74.51% of total variance, indicating a

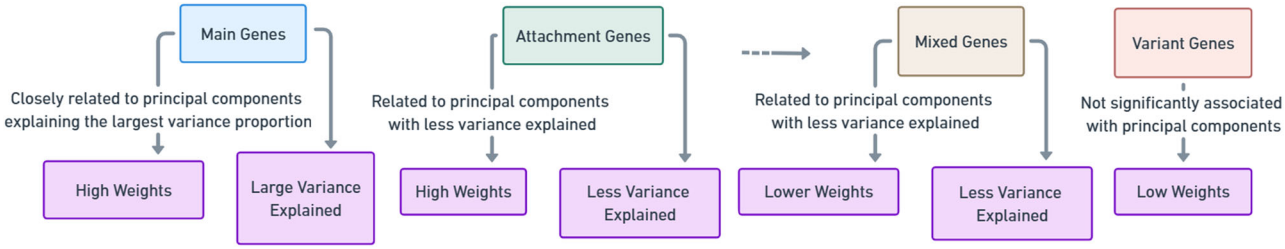


Fig. 11 | Criteria for determining genotypes of landscape elements (self - drawn).

strong statistical correlation. However, in the AHP evaluation, religious belief received higher scores in dimensions such as cultural functionality and institutional stability, marking it as a Main gene for its foundational role in shaping spatial logic, institutional frameworks, and spiritual order in Tibetan villages. In contrast, although a religious sect shares a similar statistical profile, its cultural significance is more localized and historically contingent, leading to a lower expert-assigned weight and its classification as an Attachment gene.

"Religious belief", as a cultural core, not only informs spatial generation mechanisms but also influences architecture, community structure, and ritual practices. Likewise, variables like "Building features and traditional arts" are also categorized as Attachment genes, reflecting their supportive roles in everyday practices and in sustaining cultural diversity.

"Language and text", though showing only moderate statistical loadings in PCA, was assigned a higher cultural value in the AHP due to its heritage significance and adaptability to sociocultural transitions. It was thus identified as a Mixed gene, representing continuity and flexibility in intercultural communication. Similarly, "water system layout" exhibited notable loadings across multiple components and was initially categorized as a Mixed gene. Although its expert evaluation score was moderate, its enduring influence on village morphology, irrigation systems, and spatial governance led to its reclassification as an Attachment gene.

By contrast, "village size" was marked as a Variant gene due to its weak statistical correlation and high sensitivity to external socio-economic and environmental fluctuations[12,101]. As illustrated in Fig. 12b, some variables, including "water system layout", "language and text", and "traditional art forms", shifted in gene classification based on their final weight values, highlighting the evolution from purely statistical categorization toward a more holistic evaluative framework.

This classification correction highlights the dynamic role and interactive structure of variables within the Tibetan cultural landscape. The mixed and variant genes demonstrate the tension between tradition and adaptation, while the stability of the main genes and attached genes provides structural support for the reproduction of village community culture and spatial order. Over time, these cultural genes not only carry historical continuity but also promote cultural renewal, allowing Tibetan villages to retain their artistic essence and cultural identity while responding to external changes.

Through this integrated analytical approach, the study constructs a structured and hierarchical system for classifying cultural landscape variables[102]. This not only sharpens the accuracy in identifying each variable's functional role but also offers a solid theoretical and practical base for understanding how a wide range of cultural factors interact. Ultimately, it contributes to a deeper grasp of what sustains the resilience and long-term vitality of rural Tibetan communities[103,104].

Commonalities and differences in the cultural landscape of the village

This section utilizes the information gathered from the field study and interviews, as well as the previous exploration of the genotypes of landscape elements, to map the network structure (Based on Eqs. (7–8)) and demonstrate the connections and distinctions between the villages (shown in Fig. 13). Religious beliefs as subject genes are integral to cultural identity, enhancing community cohesion and maintaining social order[105]. This influence is prominent in the spatial arrangement and architectural layout design during religious activities and traditional festivals, which are crucial for the transmission of tradition and community strengthening. Despite the diversity in religious sects, there is a uniformity in the values expressed through various religious activities, ranging from temple ceremonies to the creation of shrines and prayer rooms in homes[106].

Festivals like the "Buddha Sunning Festival" and the Tibetan New Year, although different in execution, share a common spiritual and cultural foundation. These events enhance the stability and continuity of village culture, reinforcing a shared cultural identity. The architectural style also displays significant similarities across villages, as seen in the types of buildings, decorative elements, and functional designs. For example, temples in villages such as Re La, Shen Zuo, and Xi Suo share a foundational faith that influences their spatial layouts. Although architectural details differ, all villages employ adaptations suitable for the high-altitude environment, such as heavy roofing and adequate insulation. These choices reflect a prudent adaptation to complex climates while supporting traditional family and agricultural lifestyles[107]. The architecture is shaped by geographical, historical, and climatic factors, allowing each village to develop distinct cultural characteristics and evolutionary paths[108].

Under the influence of mixed and attachment genes, villages exhibit both diversity and unique traits. Traditional clothing styles vary significantly among them. For example, Tibetan attire in Shen Zuo Village features minimalist decoration and a subdued color palette, contrasting sharply with the vibrant, ornate clothing of the Jiarong Tibetans in Xi Suo Village. Moreover, the layout and modeling of the dwellings in these villages are also unique, reflecting a respect for the natural landscape and geographical environment while also demonstrating functionality and cultural significance[109].

Language diversity in the villages also highlights cultural exchange and nuances of independence. All villagers speak Tibetan, yet tribal dialects show remarkable vocabulary and grammar differences due to geographical isolation and historical migration. These dialects offer more than just linguistic variety—they encapsulate unique cultural insights and descriptions of social phenomena and the natural environment, serving as an intangible cultural heritage that enlightens us about historical interactions and communication styles between villages[110].

Moreover, socio-economic developments and policy initiatives continue to reshape the cultural landscape of these villages, which needs to be a point of concern in subsequent studies. At the same time, integrating traditional practices with modern influences and infrastructure has led to the emergence of new cultural identities and shaped social and economic dynamics. These changes present challenges and opportunities that require a careful balance between cultural preservation and development[111].

This deep dive into the cultural landscape genes of Tibetan villages in Western Sichuan unveils their complex cultural fabric and highlights the critical need to protect and evolve these unique heritages in the face of modernization. This exploration reveals the rich cultural complexity and the ongoing conservation challenges these villages encounter during modernization.

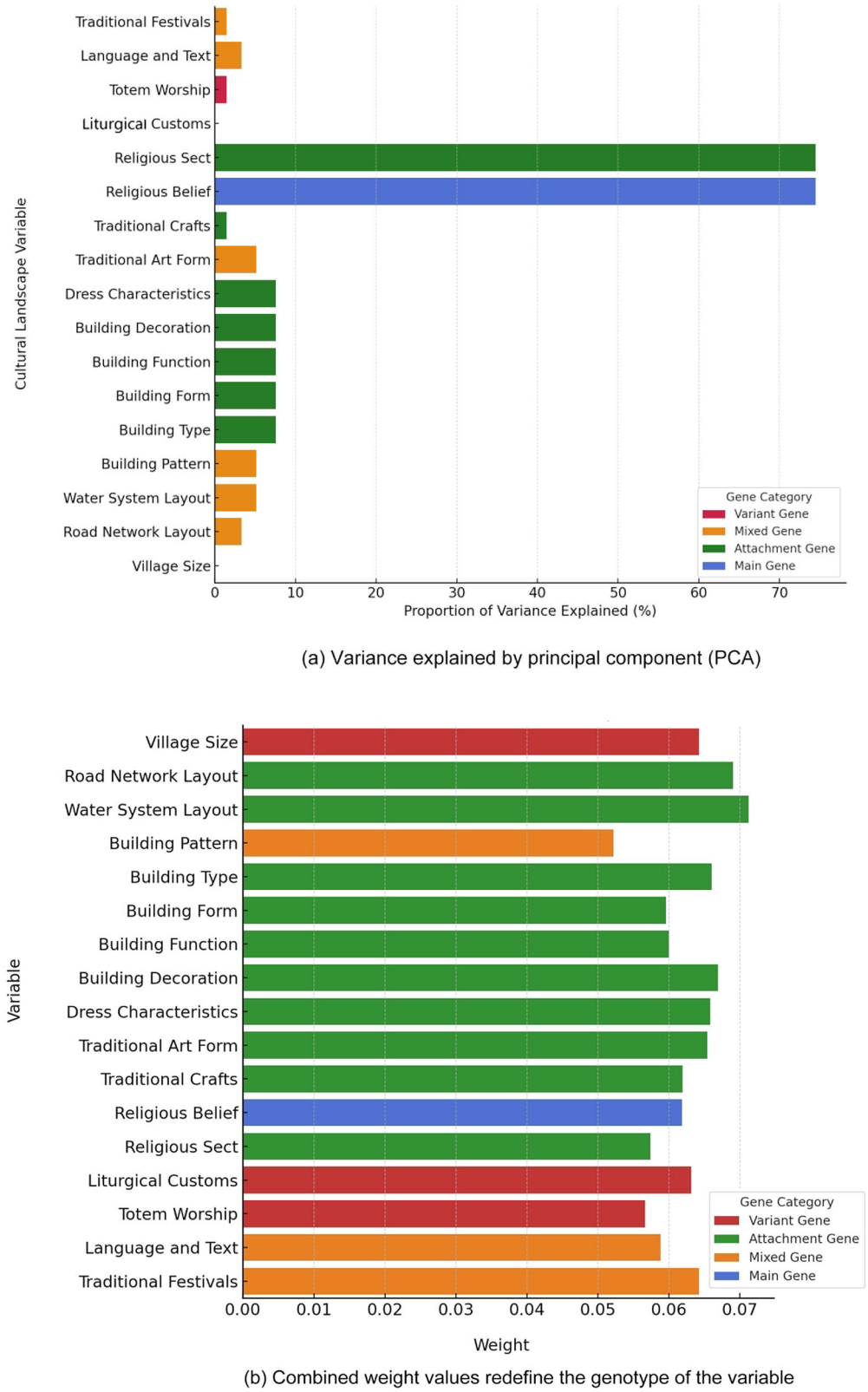


Fig. 12 | Interpretation of genotypes of variables based on PCA and AHP. a Variance explained by principal component(PCA); **b** Combined weight values redefine the genotype of the variable.

Cultural landscape heritage and challenges in Tibetan villages

Cultural landscapes are a central component of cultural heritage, encompassing rich histories and diverse artistic expressions. These landscapes are vital for education and community engagement, promoting the younger generation's appreciation of the uniqueness and diversity of local culture. However, they face threats from foreign cultural influences and modern lifestyles that undermine their traditional features and essence[112].

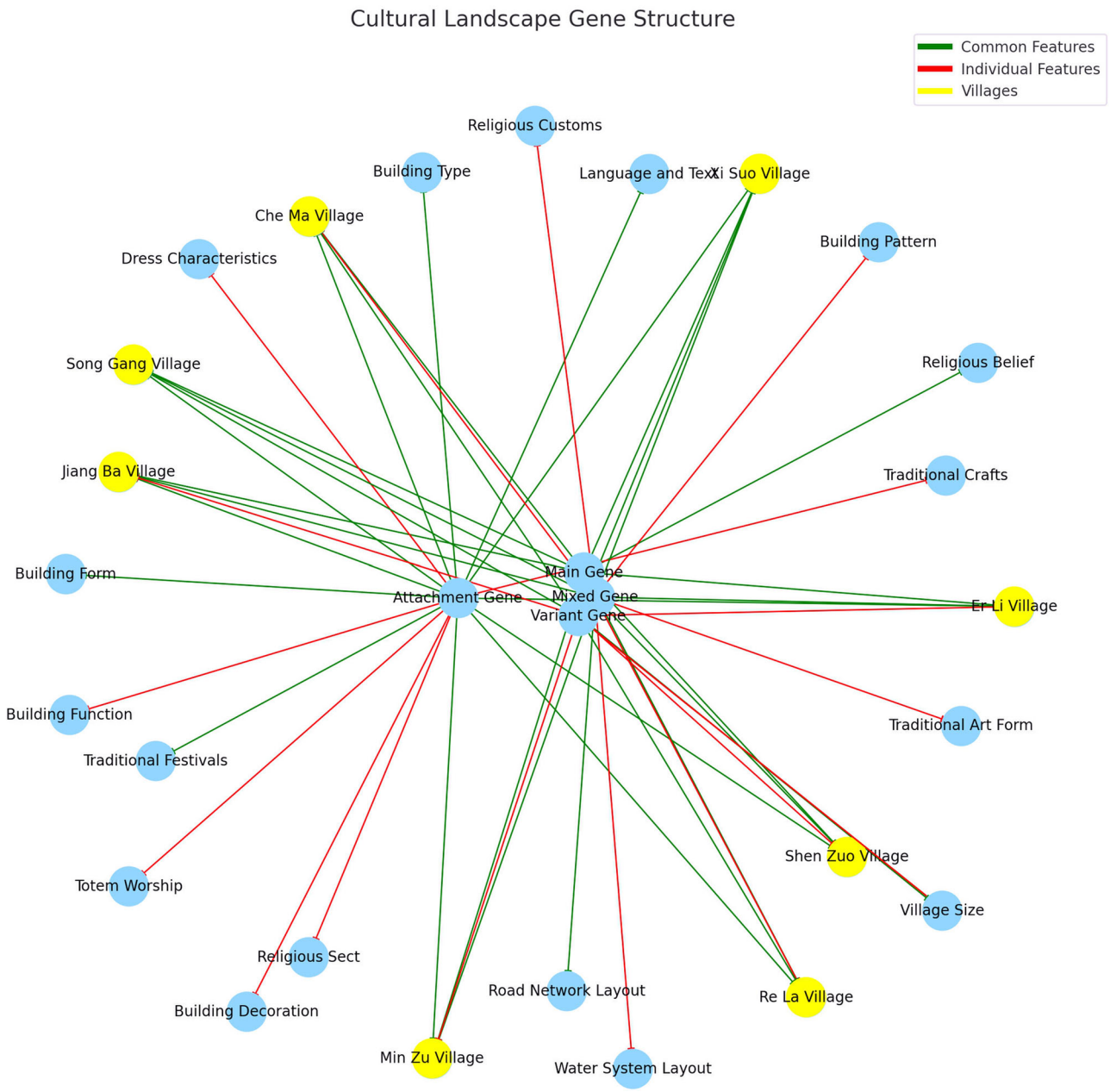


Fig. 13 | Analyzing network structure.

Community education programs are crucial in this context. During field visits, interactions with local communities revealed a deep respect for traditional cultural systems, emphasizing the importance of oral histories and artisanal skills vital for preserving cultural continuity. Incorporating these Traditional forms of knowledge transmission into formal education can strengthen community cohesion and preserve unique cultural identities[105]. Cultural practices, rituals, and festivals foster a sense of identity and belonging, serving as mechanisms for social cohesion and intergenerational communication[108,110]. Our field research highlighted the prominent role of these cultural expressions in community life, shaping the social fabric and fostering cultural continuity in the face of a changing external environment.

Addressing these challenges requires a stronger focus on the sustainability of cultural landscapes. Field research and data analysis have provided essential insights into the geographical environment, community development, and artistic preservation. In traditional Tibetan villages, natural features such as mountains, rivers, and forests shape the physical layout and communities' cultural and social structures. Water sources and terrain significantly shape residents' daily activities, architectural styles, and road networks. These natural conditions underpin the villages' self-sufficiency and sustainable growth, prioritizing them for preservation[113]. Our analyses enhance understanding of the complexity and diversity involved in preserving cultural landscapes, enabling the creation of protective measures that balance tradition and modern needs.

Conservation efforts should prioritize the sustainability of the natural environment and its role in supporting traditional practices, thereby providing crucial data for further research. A multifaceted approach is recommended, including the establishment of community workshops, cultural festivals, and the revival of traditional crafts to enhance community engagement and secure policy support[114,115]. Furthermore, integrating local cultural and environmental research into community education and media outreach raises public awareness of the need to preserve both cultural and natural environments[116]. Striking a balance between heritage conservation and development is essential[117,118]. Sustainable practices that respect

traditional methods are essential, such as utilizing modern building techniques to preserve traditional structures and leveraging cultural and ecological benefits to enhance local landscapes[119,120].

Preserving and developing cultural landscapes in Tibetan villages requires extensive community participation, robust policy support, and regional collaboration. This comprehensive strategy both safeguards and rejuvenates unique cultural heritages[121]. Studying the cultural genome of these landscapes enables the preservation of Tibetan village culture-s'authenticity and the development of strategies to address contemporary challenges.

Discussion

This study integrates gene identification techniques with GIS spatial analysis and extensive field research to systematically investigate the cultural landscape of traditional Tibetan villages in western Sichuan. By categorizing cultural landscape genes into core, attachment, mixed, and variant types, this research establishes a structured and replicable framework enabling multidimensional analysis of cultural landscapes across levels such as units, hierarchies, coding, and categorization[122,123]. This methodological integration significantly advances the understanding of cultural genotypes and their essential role in preserving the authenticity and diversity of village cultures[124].

The findings reveal that various gene types have distinct roles in shaping the cultural landscape. Core genes, such as religious beliefs, serve as the cultural backbone, shaping spatial organization, architectural styles, and community rituals. Attachment genes, such as architectural features and traditional arts, provide stability and enhance the cultural landscape through daily practices and craftsmanship. Mixed genes, such as language and festivals, demonstrate the adaptability of Tibetan culture, reflecting its evolution through cross-cultural interactions. Variant genes, such as village size, illustrate the community's adaptability to socio-economic and environmental changes. These findings provide a nuanced understanding of the interplay between tradition and adaptation, offering fresh perspectives on the dynamics of cultural landscapes[125–127].

This research advances the theoretical understanding of cultural landscape genetics by establishing a robust framework that integrates spatial and cultural dimensions. It highlights the essential role of cultural norms and symbols in sustaining community resilience under globalization pressures and proposes practical strategies for preserving cultural heritage. Furthermore, the study emphasizes the need to balance the preservation of tangible and intangible cultural elements to sustain cultural diversity and promote the sustainable development of ethnic communities. Enriching existing methodologies provides a replicable model for analyzing cultural landscapes in other ethnic areas, bridging theoretical insights and practical applications in heritage conservation.

Despite its contributions, this study acknowledges certain limitations. The research scope was limited to a small number of Tibetan villages, which may constrain the generalizability of the findings. A broader survey encompassing more communities and diverse cultural landscapes could yield a more comprehensive understanding. Additionally, the cross-sectional nature of this study does not capture long-term cultural dynamics, such as the impacts of policy changes and economic development on cultural landscapes[42,44]. Future research should extend the application of this framework to encompass a broader range of villages and integrate additional variables, such as socio-economic, environmental, and policy factors. Longitudinal studies would also be valuable for capturing the temporal evolution of cultural landscapes, offering a dynamic perspective on cultural adaptation and resilience. These efforts will enhance the applicability and depth of the findings, establishing new benchmarks for cultural heritage conservation research[114,128–130].

Based on a systematic analytical framework, this article explores the role of tangible and intangible cultural elements in shaping and maintaining village identity. It comprehensively depicts the environmental, social, and cultural dimensions of Tibetan tribal villages. It elucidates how these dimensions interact to preserve the integrity and resilience of ethnic cultures, ensuring their continuity amidst modernization. The study provides empirical support for the theoretical development of cultural landscape genetics. Additionally, it establishes a strong foundation for developing more precise and feasible strategies for conserving cultural heritage. These strategies emphasize the protection of cultural heritage and its flexible and sustainable integration into contemporary social development. The findings further confirm that cultural landscape genes play a central role in safeguarding and perpetuating the traditions of ethnic rural communities, highlighting their critical importance in maintaining cultural diversity and long-term resilience.

Data availability

The raw datasets collected for this study are available on platforms such as the Sichuan Provincial Statistical Yearbook(https://www.zgtjnj.org/navisearch-2-0-3-1-sichuan-0.html), Institute of Geographical Sciences and Nature Resources Research (https://igsnrr.cas.cn/); Chinese Academy of Sciences (https://www.cas.ac.cn), and the Chinese Traditional Villages website(http://www.chuantongcunluo.com). The base map is sourced from OpenStreetMap contributors and used under the Open Database License (ODbL), available at https://www.openstreetmap.org/copyright. The relevant platform's access procedure can access these datasets upon request.

Received: 22 November 2024; Accepted: 11 June 2025;
Published online: 04 July 2025

References

1. Liu, J., Wang, Z., & Chen, X. (2022). Spatial distribution characteristics and influencing factors of traditional villages on the Tibetan Plateau in China. *Int. J. Environ. Res. Public Health*, 19, 13170. https://www.mdpi.com/1660-4601/19/20/13170/pdf?version=1666685484.
2. Fan, D., Maliki, N. Z. B. & Yu, S. Fractal characteristics and influencing factors of landscape space of Tibetan rural in Western Sichuan: a case study of three traditional villages. *Front. Urban Rural Plan.* **1**, 22 (2023).
3. Coggins, C. & Hutchinson, T. The political ecology of geopiety: Nature conservation in Tibetan communities of northwest Yunnan. *Asian Geogr.* **25**, 85–107 (2006).
4. Nie, K. C. Study on the spatial organization mechanism and simulated evolution of Tibetan Buddhist Monastic Settlements on the Western Sichuan Plateau. *J. Civil Eng. Urban Planning*. ISSN 2616-3969 Vol. 5 Num. 4. https://doi.org/10.23977/jceup.2023.050406 (2023).
5. Sakketa, T. G. Urbanization and rural development in sub-Saharan Africa: A review of pathways and impacts. *Res. Globalization*, 100133. https://doi.org/10.1016/j.resglo.2023.100133 (2023).
6. Herrero-Jáuregui, C. & Concepción, E. D. Effects of counter-urbanization on Mediterranean rural landscapes. *Landsc. Ecol.* **38**, 3695–3711 (2023).
7. Dang, A., Zhao, D., Chen, Y., & Wang, C. (2020). Conservation of cave-dwelling village using Cultural Landscape Gene Theory. Spatial synthesis: Computational social science and humanities, 97-105. https://doi.org/10.1007/978-3-030-52734-1_8.
8. Mu, Q. & Aimar, F. How are historical villages changed? A systematic literature review on European and Chinese cultural heritage preservation practices in rural areas. *Land* **11**, 982 (2022).
9. Jin, Z. Traditional villages conservation of Ganzi Tibetan Area: A study in perspective of cultural consciousness. *DEStech Trans. Soc. Sci., Educ. Hum. Sci.* https://doi.org/10.12783/DTSSEHS/HSMET2017/16551 (2017). ISBN: 978-1-60595-494-3.
10. Dong, S. Revitalizing the grassland on the Qinghai–Tibetan Plateau. *Grassl. Res.* **2**, 241–250 (2023).

11. Jiang S, et al. Genetic analysis and protection strategy of cultural landscape of Jiajung Tibetan Traditional Villages from the perspective of landscape gene. *Proc. World Habitat Sci. Dev. Forum*. 151-156 (2020).
12. Li, T., Li, C., Zhang, R., Cong, Z. & Mao, Y. Spatial heterogeneity and influence factors of traditional villages in the Wuling Mountain area, Hunan Province, China based on Multiscale Geographically Weighted Regression. *Buildings* **13**, 294 (2023).
13. Song, X. & Zhang, N. Construction of genetic map of traditional rural landscape of Hehuang Region, Qinghai Province. *Residential Sci. Technol.* **04**, 37–43 (2021).
14. Cai, P., & Xu, Z. (2024). A Study on Strategies for Cultural Landscape Enhancement of Traditional Villages Based on Landscape Gene Theory. In 3rd International Conference on Culture, Design and Social Development (CDSD 2023) (pp. 439-452). Atlantis Press.
15. Rössler, M. & Lin, R. C. H. Cultural landscape in world heritage conservation and cultural landscape conservation challenges in Asia. *Built Herit.* **2**, 3–26 (2018).
16. Hu, Z., Josef, S., Min, Q., Tan, M. & Cheng, F. Visualizing the cultural landscape gene of traditional settlements in China: a semiotic perspective. *Herit. Sci.* **9**, 1–19 (2021).
17. Li, B. H., Li, Z., Liu, P. L. & Dou, Y. D. Genetic variation and divergence patterns of traditional village landscapes in the Xiangjiang River Basin. *J. Nat. Resour.* **37**, 362–377 (2022).
18. Munshi-South, J. & Richardson, J. L. Landscape genetic approaches to understanding movement and gene flow in cities. *Urban evolutionary biology*, 54–73, https://doi.org/10.1093/oso/9780198836841.003.0004 (2020).
19. Agnoletti, M., Piras, F., Venturi, M. & Santoro, A. Cultural values and forest dynamics: The Italian forests in the last 150 years. *Ecol. Manag.* **503**, 119655 (2022).
20. Wei, X. (2019). Research and study on village landscape genetic characteristics in minority area-with Tibet and Qiang watchtower village in west Sichuan region as an example. In IOP Conference Series: Earth and Environmental Science (Vol. 267, No. 5, p. 052063).
21. Yan S. Adaptation of Contemporary Tibetan Local Culture from the Perspective of the Tibetan Population Ph.D. (Dissertation, Lanzhou University). https://link.cnki.net/doi/10.27204/d.cnki.glzhu.2020.000100, https://doi.org/10.27204/d.cnki.glzhu.2020.000100 (2020).
22. Hu, M. C., Fu, H., Geng, T. Y. & Tseng, A. J. A study on landscape gene identification of traditional Tibetan villages in Jiuzhaigou County. *Archit. Cult.* **05**, 211–212 (2022).
23. LIN L., TIAN J., ZHONG Z., LI S., REN B. Protection and renewal of traditional villages from the perspective of cultural gene: A case study of Northeast Guizhou Tujia Minority. *Trop. Geogr.*, 38:413-423. (2018).
24. JIANG S.H., FAN Y.M., ZHENG W.J. Research progress on landscape's gene theory and its utilization in China. *J. Human Settlements West China*, 36: 84-91. (2021).
25. Yang, M., Wen, J., Jiao, M. & Xiao, L. The impact of integrating agriculture and tourism on poverty reduction in China's Ethnic Minority Areas. *J. Int. Dev.* https://doi.org/10.1002/jid.4009 (2025).
26. Xiang Y., Cao M., Qin J., Wu C. A study on landscape genetic variability of traditional rural settlements in Shaanxi based on precision restoration. *Adv. Geogr. Sci.* 39: 1544-1556 (2020).
27. Wang, X., Jin, X. & Feng, Y. Landscape reconstruction of traditional village couplets based on image recognition algorithm. *J. Opt.* **52**, 224–232 (2023).
28. Liu, P., Zeng, C. & Liu, R. Environmental adaptation of traditional Chinese settlement patterns and its landscape gene mapping. *Habitat Int.* **135**, 102808 (2023).
29. Yin Z. & Li J. Landscape Gene Identification and Mapping Construction of Historical and Cultural Villages and Towns--Taking Huangpi Dayuwan as an Example. Urban Planning.08,8-18. https://kns.cnki.net/kcms/detail/11.2378.TU.20220803.1601.002.html, (2022).
30. Li H. Toward a Modern and Difficult "Transformation" on Alai's Ecological Writing, Doctoral Dissertation, Zhejiang University (2018).
31. Li, Z. et al. Research on the spatial correlation and formation mechanism between traditional villages and rural tourism. *Sci. Rep.* **13**, 8210 (2023).
32. Pasquale, G. & Spinelli, E. The alpine rural landscape as a cultural reserve: the case study of Teglio in Valtellina. *Biodivers. Conserv.* **31**, 2397–2420 (2022).
33. Sachaleli, N. Sustainability as a competitive advantage in rural tourism development. *Agric. Econ. Rural Dev.* **20**, 41–52 (2023).
34. Zhang, Q., Kim, E., Yang, C. & Cao, F. Rural revitalization: sustainable strategy for the development of cultural landscape of traditional villages through optimized IPA approach. *J. Cultural Herit. Manag. Sustain. Dev.* **13**, 66–86 (2023).
35. Qin, Z., & Yang, B. Research of Protection and Development of Regional Culture Against the Background of Tourism Development: Taking Jiaju Tibetan Village, Danba County, Sichuan Province as an Example, 450-453. (2020).
36. Orphanidou, Y., Efthymiou, L. & Panayiotou, G. Cultural heritage for sustainable education amidst digitalisation. *Sustainability* **16**, 1540 https://doi.org/10.3390/su16041540 (2024).
37. Ramisa, S., Dora, M. Using Mixed Methods to Understand Spatio-Cultural Process in the Informal Settlements: Case Studies from Islamabad, Pakistan. Humans, 2:259-276. (2022).
38. Indah, R. Qualitative interview with sensitive participants. *J. Pendidik. Kedokt. Indones.* **11**, 22–22 (2022).
39. Masoumeh, R. Interviewing: The most Common Methods of Data Collection in Qualitative Studies. Sadra Medical Sciences Journal, 6:303-316. (2018).
40. Sandra, L. Conducting interviews for qualitative research studies. *Clin. Nurse Specialist* **36**, 78–80 (2022). Siedlecki.
41. Mavhandu-Mudzusi, A. H. et al. WhatsApp as a qualitative data collection method in descriptive phenomenological studies. *Int. J. Qualit. Methods* **21**, 16094069221111124 (2022).
42. Bergen, N. & Labonté, R. "Everything is perfect, and we have no problems": detecting and limiting social desirability bias in qualitative research. *Qualit. health Res.* **30**, 783–792 (2020).
43. Mirhosseini, S.-A. (2020). Collecting Interview Data. 85-109.
44. Terkenli, T. S., Gkoltsiou, A. & Kavroudakis, D. The interplay of objectivity and subjectivity in landscape character assessment: Qualitative and quantitative approaches and challenges. *Land* **10**, 53 (2021).
45. Maragno, G., Tangi, L., Gastaldi, L. & Benedetti, M. Exploring the factors, affordances and constraints outlining the implementation of Artificial Intelligence in public sector organizations. *Int. J. Inf. Manag.* **73**, 102686 (2023).
46. Liu, F. & Meng, K. Analysis of geomorphic environment elements and landscape features of cultural administrative place names. *Arab. J. Geosci.* **14**, 1–10 (2021).
47. Chmiel, J. Cultural landscape as both a threat and an opportunity to preserve a high conservation value of vascular flora: A case study. *Diversity* **15**, 211–211 (2023).
48. Cao, K., Liu, Y., Cao, Y., Wang, J. & Tian, Y. Construction and characteristic analysis of landscape gene maps of traditional villages along ancient Qin-Shu roads, Western China. *Herit. Sci.* **12**, 37 (2024).
49. Yang, L., Hu, Y. L., Wu, X. F. & Hu, J. Processes and mechanisms of cultural landscape gene production in traditional villages - A case study of Huangdu Village. *J. Nat. Resour.* **38**, 1164–1177 (2023).
50. Jialuo, L., Tang, L. & Li, A. Construction of landscape gene mapping and its characteristics in Furong Town, Xiangxi. *Mod. Horticulture* **23**, 117–123 (2022).

51. Wang, T., Youde W., Can-Song L., Jun L., Changyao C., Xurui G., & Yus L. Genetic information chain and bionic modeling of geographical names and cultural landscapes: An Example of the Geographical Names of the South China Sea Islands. World Regional Studies, 32. https://doi.org/10.3969/j.issn.1004-9479.2023.10.20230103 (2023).
52. Pichkar, Y. & Creanza, N. Fine-scale cultural variation reinforces genetic structure in England. *Am. J. Biol. Anthropol.* **181**, 626–636 (2023).
53. Wang, C., Zhong, H. & Chestnut, W. B. Gene identification and genealogy construction of the cultural landscape of settlements - A case study of Dong traditional villages in Guibei. *Soc. Scientist* **2**, 50–55 (2022).
54. Chen, S. Q. & Zhang, Y. J. Advances in rural landscape biodiversity research. *Biodiversity* **29**, 1411–1424 (2021).
55. Chen, B. & Pang, Y. Spatial production mechanism and scenario expression of the yellow river national cultural park. *J. Wuhan. Univ. (Philos. Soc. Sci. Ed.)* **5**, 66–80 (2022).
56. Khalaf, R. W. Continuity: A fundamental yet overlooked concept in World Heritage policy and practice. *Int. J. Cult. Policy* **27**, 102–116 (2021).
57. Pless, E., Saarman, N. P., Powell, J. R., Caccone, A. & Amatulli, G. A machine-learning approach to map landscape connectivity in Aedes aegypti with genetic and environmental data. *Proc. Natl Acad. Sci.* **118**, e2003201118 (2021).
58. Shrestha, N. Factor analysis as a tool for survey analysis. *Am. J. Appl. Math. Stat.* **9**, 4–11 (2021).
59. Wen, B. & Burley, J. B. Expert opinion dimensions of rural landscape quality in Xiangxi, Hunan, China: Principal component analysis and factor analysis. *Sustainability* **12**, 1316 (2020).
60. Li, Q., Wumaier, K. & Ishikawa, M. The spatial analysis and sustainability of rural cultural landscapes: Linpan settlements in China's Chengdu Plain. *Sustainability* **11**, 4431 (2019).
61. Du, Y. W. & Li, X. X. Hierarchical DEMATEL method for complex systems. *Expert Syst. Appl.* **167**, 113871 (2021).
62. Wang, X., Meng, Q., Zhang, L. & Hu, D. Evaluation of urban green space in terms of thermal environmental benefits using geographical detector analysis. *Int. J. Appl. Earth Obs. Geoinf.* **105**, 102610 (2021).
63. Mathwich, N. M. & Giomi, E. Order on the edge of empire: social network analysis of colonial mission landscapes in Nuevo México and the Pimería Alta. *Int. J. Historical Archaeol.* **26**, 474–497 (2022).
64. Sokolova, A. (2021). Settlements network and communications in the structure of the information frame of the Verhneoredezhsky cultural landscape. *Pskov J. Regl. Stud.* 92-106.
65. Liu, Q., Hao, W. & Xia, M. Spatial association of coastal towns and villages in Funing District, Qinhuangdao: A study using social network analysis. *J. Rural Stud.* **107**, 103261 (2024).
66. Su, X. Sociological Study of Interaction Between Temple and Community in Tibetan-Related Areas. In The 7th International Conference on Contemporary Education, Social Sciences and Humanities (Philosophy of Being Human as the Core of Interdisciplinary Research) (ICCESSH 2022) (pp. 73-81). Atlantis Press (2022).
67. Li, G., Chen, B., Zhu, J. & Sun, L. Traditional Village research based on culture-landscape genes: a Case of Tujia traditional villages in Shizhu, Chongqing, China. *J. Asian Archit. Build. Eng.* **23**, 325–343 (2024).
68. Xiong W. Genetic and variation analysis studies on landscape genes of traditional Tibet and Qiang watchtower villages in western Sichuan. In IOP Conference Series. Earth and Environmental Science (Vol. 310, No. 2). IOP Publishing (2019).
69. Chao, Z., Zhao, Y. & Liu, G. Multi-scale spatial patterns of Gelugpa monasteries of Tibetan Buddhism in Tibetan Inhabited Regions, China. *GeoJournal* **87**, 4289–4310 (2022).
70. Wang, P.W., Jinhe Z., Feng S., Shanshan C., Yue K., Chang W., & Dong X. Spatial distribution characteristics of traditional villages in southwest China and their influence mechanisms. *Econ. Geogr.* **41**, 204-213. (2021).
71. Qin, S., Li, X., Chen, W. & Zhang, C. Geospatial patterns and influential factors of ethnic minority characteristic villages in the Yangtze River Economic Belt. *Hum. Geogr.* **37**, 118–130 (2022).
72. Winfield, P. D. The Philosophy of the Mandala. The Dao Companion to Japanese Buddhist Philosophy, 235-253. (2019).
73. Fang, Q., & Li, Z. Cultural ecology cognition and heritage value of Huizhou traditional villages. Heliyon, 8. http://creativecommons.org/licenses/bync-nd/4.0/, (2022).
74. Wang J. Research on the status quo of landscape ecological resources of Moya Tibetan traditional villages--Taking Kaganba Lize Village in Kangding City, Ganzi Prefecture as an Example. Housing and real estate, :253-254 (2021).
75. Hou, X. & Shi, J. Analysis on the symbolic system of twelve-phase Tibetan Mask in Baima of Pingwu County. *Open Access Libr. J.* **8**, 1–7 (2021).
76. Chen, G. *A Survey and Research on the Ershu Tibetans*. Ethnic Press. pages 298. ISBN: 978-105-16185-0 (2020).
77. Zhang, Q., Kim, E., Yang, C. & Cao, F. Rural revitalization: A sustainable strategy for the development of the cultural landscape of traditional villages through optimized IPA approach. *J. Cult. Herit. Manag. Sustain. Dev.* **13**, 66–86 (2023).
78. Amudha, B., Srivastava S. Redefining the purpose of Tibetan arts and crafts in interiors. *J. Emerg. Technol. Innov. Res.* 7:1819-1821-1819-1821 (2020).
79. Zhang, Y. The role and practices of traditional culture in The Tibetan Plateau Ecosystem: A systematic review. *Highlights Sci., Eng. Technol.* **17**, 128–132 (2022).
80. Ptackova J. Traditionalization as a response to state-induced development in rural Tibetan areas of Qinghai, PRC. In Practices of Traditionalization in Central Asia (pp. 108-122). Routledge (2020).
81. Woodhouse E., Martin, M. A., McGowan. Philip, J. K., Milner-Gulland E. J. Religious Relationships with the Environment in a Tibetan Rural Community: Interactions and Contrasts with Popular Notions of Indigenous Environmentalism. *Human Ecology* 43:295-307. (2015).
82. Li, T. Y., & Li, J. H. (2017). An analysis of the conservation and development strategies of the residential houses of the Gotun Tibetan community under the influence of history and religious culture. Architecture and Culture, 230-232. http://www.cqvip.com/qk/87551x/201705/672089463.html.
83. Lee, S. S. Buddhist art and architecture. *Oxf. Res. Encycl. Asian Hist.* https://doi.org/10.1093/acrefore/9780190277727.013.398 (2020).
84. Ji, Y. et al. Symbolism, use, and knowledge of birds in tibetan communities of China. *Soc. Anim.* **31**, 281–306 (2022).
85. Ling, X., & Chen, F. (2019). The Development Trend of Tibetan Decorative Art and Boudoir Architecture Integration and Cultural Tourism under the Background of Big Data. In 2019 4th International Conference on Mechanical, Control and Computer Engineering (ICMCCE) (pp. 685-6853). IEEE.
86. Nyima, T. & Suzuki, H. Newly recognized languages in Chamdo: Geography, culture, history, and language. *Linguist. Tibet. -Burma area* **42**, 38–81 (2019).
87. The Great Tibetan Book of Ganjur and Tanjur. (2019). https://www.163.com/dy/article/EPML9LMI05418RHB.html.
88. Mu-fan, G., Ju-Yeon, K. Transmission plan of Guozhuang Dance in Jiarong Manai, Sichuan Province, China. The Korean Society of Sports Science, 31:779-790. (2022).
89. Jian, L. I. U. & Yue, W. E. I. A Study on the Values and Strategies of Transmission of Tibetan Traditional Sports Culture in" Great Shangriâ€"La". *DEStech Trans. Soc. Sci., Educ. Hum. Sci.* https://doi.org/10.12783/DTSSEHS/EELSS2020/34591 (2020).

90. Ce, Q., Timothy, D.J., Zhang C. Does tourism erode or prosper culture? Evidence from the Tibetan ethnic area of Sichuan Province, China. *J. Tourism Cult. Change*, 17:526-543. (2019).
91. Jakub, J., Markéta, Š., Marek, K. Typology of historical cultural landscapes based on their cultural elements. *Geografie*, 126:243-261. (2021).
92. Packard J.M., Priscilla, W., Paolisso M., Srinivasan M. Use of principal components analysis to assess cultural models of land conservation. *F1000Research*, 1 https://doi.org/10.7490/F1000RESEARCH.293.1 (2010).
93. Dina T., Grunewald., I.B. Cultural landscapes as a model for natural and human systems integration. *South African J. Art History*, 28:51-76. https://hdl.handle.net/10520/EJC149228, (2013).
94. Zhao, J. et al. A review of statistical methods for dietary pattern analysis. *Nutr. J.* **20**, 1–18 (2021).
95. Krenický, T., Hrebenyk L.I., Chernobrovchenko V.S. Application of concepts of the analytic hierarchy process in decision-making. *Manag. Syst. Prod. Eng.*, 30:304-310. (2022).
96. Težak Damijanić, A. "Wellness and healthy lifestyle in tourism settings. *Tour. Rev.* **74**, 978–989 (2019). No. 4.
97. Chen, J. et al. Soil fertility quality assessment based on geographically weighted principal component analysis (GWPCA) in large-scale areas. *Catena* **201**, 105197 (2021).
98. Nafi'Shehab, Z., Jamil, N. R., Aris, A. Z. & Shafie, N. S. Spatial variation impact of landscape patterns and land use on water quality across an urbanized watershed in Bentong, Malaysia. *Ecol. Indic.* **122**, 107254 (2021).
99. Goretzko, D., Pham, T. T. H. & Bühner, M. Exploratory factor analysis: Current use, methodological developments, and recommendations for good practice. *Curr. Psychol.* **40**, 3510–3521 (2021).
100. Muchie, G. & Belete, D. Principal component analysis for seven quantitative traits of different rice (Oryza sativa L.) genotypes tested at Pawe, northwestern Ethiopia. *Int. J. Sch. Res. Rev.* https://doi.org/10.56781/ijsrr.1.1.0022 (2022). 01(01),009-016.
101. Zhang J., Zhao Y., He Y., Wang M., & Cai B. Evolutionary characteristics and spatial relationships of rural multifunctionality in Henan Province. *Econ. Geogr.*, **42**, 122-132. (2023).
102. Zhou, J., Li, J., Ma, Q. R. & Huang, X. J. Special body shape sample identification based on improved hierarchical analysis. *Text. J.* **40**, 124–130 (2019).
103. Smolla, M., & Akçay, E. Pathways to cultural adaptation: the coevolution of cumulative culture and social networks. Evolutionary Human Sciences, 5. https://doi.org/10.1101/2023.02.21.529416 (2023).
104. Fogarty, L., & Kandler, A. The fundamentals of cultural adaptation: implications for human adaptation. Scientific Reports, 10. https://doi.org/10.1038/s41598-020-70475-3 (2020).
105. Alonzo, G. & Rossetti, G. Festivals as instruments of cultural welfare: A theoretical reflection. Welfare e Ergonomia https://doi.org/10.3280/we2023-001003 (2023).
106. Suardana, I. W., Gelgel, I. P. & Watra, I. W. Traditional villages empowerment in local wisdom preservation towards cultural tourism development. *Int. J. Soc. Sci.* **5**, 74–81 (2022).
107. Wang, J., Seyler, B. C., Phuntsok, T. S., Lu, Y. & Tsomo, L. Traditional beliefs, culture, and local biodiversity protection: An ethnographic study in the Shaluli Mountains Region, Sichuan Province, China. *J. Nat. Conserv.* **68**, 126213 (2022).
108. Nuruddin, N. Local wisdom as social cohesion in establishing inter-religious life in Donggo, district of Bima. *SANGKéP: J. Kaji. Sos. Keagamaan* **5**, 88–96 (2022).
109. Shi, Z., Ma, L., Zhang, W. & Gong, M. Differentiation and correlation of spatial pattern and multifunction in rural settlements considering topographic gradients: Evidence from Loess Hilly Region, China. *J. Environ. Manag.* **315**, 115127 (2022).
110. Ezzy, D. et al. Religious Diversity in Australia: Rethinking Social Cohesion. *Religions* https://doi.org/10.3390/rel11020092 (2020).
111. Singh, P. et al. Time investments in rituals are associated with social bonding, affect and subjective health: A longitudinal study of Diwali in two Indian communities. *Philos. Trans. R. Soc. B*, **375**. https://doi.org/10.1098/rstb.2019.0430 (2020).
112. Yang, H., Qiu, L. & Fu, X. Toward cultural heritage sustainability through participatory planning based on investigation of the value perceptions and preservation attitudes: Qing Mu Chuan, China. *Sustainability* **13**, 1171 (2021).
113. Cui, N., Zou, H., Zhang, M. & Guo, L. The effects of terrain factors and cultural landscapes on plateau forest distribution in Yushu Tibetan Autonomous Prefecture, China. *Land* https://doi.org/10.3390/LAND10040345 (2021).
114. Li, J., Krishnamurthy, S., Roders, A. P. & Van Wesemael, P. Community participation in cultural heritage management: A systematic literature review comparing Chinese and international practices. *Cities* **96**, 102476 (2020).
115. Xu, L. et al. Evaluating communities' willingness to participate in ecosystem conservation in Southeast Tibetan Nature Reserves, China. *Land* **11**, 207 (2022).
116. Bernardo, J., Bevilacqua Jr, V. G., Holtman, C. S., Franz, G., & Da Rocha, M. P. Parana pine landscape and social life cycle assessment (S-LCA) supporting sustainable local development: Avaliação da paisagem do pinho Paraná e do ciclo de vida social (S-LCA), apoiando o desenvolvimento local sustentável. *Braz. J. Dev.* 59787-59813. https://doi.org/10.34117/bjdv8n8-319 (2022).
117. Laalaoui, Y., Elassaoui, N., & Ouahine, O. (2024). Balancing urban growth and the sustainability of groundwater and agricultural land: Case of the bruchid-that area. In E3S Web of Conferences (Vol. 489, p. 04012). EDP Sciences.
118. Yanan, L., Ismail, M. A. & Aminuddin, A. How has rural tourism influenced the sustainable development of traditional villages? A systematic literature reviews. *Heliyon* **10**, E25627 (2024). ISSUE 4.
119. Harbiankova, A., Scherbina, E. & Budzevich, M. Exploring the significance of Heritage preservation in enhancing the settlement system resilience. *Sustainability* **15**, 15251 (2023).
120. Tang, Q. Chinese rural architecture between tradition and modernization (Doctoral dissertation, University of British Columbia). https://doi.org/10.14288/1.0431394 (2023).
121. Wang, L. Study on the stability evaluation of ecological environment in Tibet from the perspective of sustainable development, 5, 34-39. https://doi.org/10.23977/EREJ.2021.050208 (2021).
122. Dang, A., Zhao, D., Chen, Y., & Wang, C. Conservation of cave-dwelling village using cultural landscape gene theory, pp 97–105. ISBN: 978-3-030-52733-4 (2020).
123. Wu, H., Liang, T. & Shen, T. The spatial characteristics of traditional villages and their heritage protection based on landscape genes. *WSEAS Trans. Environ. Dev.* **19**, 320–328 (2023).
124. Xu, H., Zhang, T., Ge, B. & Song, Y. Developing of rural settlement landscape gene research system based on content analysis. *J. Asian Archit. Build. Eng.* **22**, 2839–2850 (2023).
125. Verschuuren, B., et al. Cultural and spiritual significance of nature: Guidance for protected and conserved area governance and management (Vol. 32). IUCN, International Union for Conservation of Nature and Natural Resour. ISBN 978-2-8317-2089-0 (2021).
126. Csurgó, B. & Smith, M. K. The value of cultural ecosystem services in a rural landscape context. *J. Rural Stud.* **86**, 76–86 (2021).
127. Khalaf, R. W. The implementation of the UNESCO World Heritage Convention: Continuity and compatibility as qualifying conditions of integrity. *Heritage* **3**, 384–401 (2020).
128. Chamling, M. & Bera, B. Spatio-temporal patterns of land use/land cover change in the Bhutan–Bengal foothill region between 1987

and 2019: study towards geospatial applications and policy making. *Earth Syst. Environ.* **4**, 117–130 (2020).
129. Labadi, S., Giliberto, F., Rosetti, I., Shetabi, L., & Yildirim, E. (2021).Ege (2021) Heritage and the sustainable development goals: policy guidance for heritage and development actors. Other. ICOMOS 134p. ISBN 978-2-918086-87-1.
130. Yutian, L. U., Sun, X. U., Songxue, L. I. U. & Jiayu, W. U. An approach to urban landscape character assessment: Linking urban big data and machine learning. *Sustain. Cities Soc.* **83**, 103983 (2022).

Acknowledgements

This research was funded by the Humanities and Social Sciences Cultivation Project, titled Adaptation and Sustainability Analysis of Cultural Landscape of Tibetan Villages in Western Sichuan under the Perspective of Ecological-Cultural Integration (Project ID: KYCXTD2024-4). 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.

Author contributions

F.D. conceptualized the study, conducted the analysis, and drafted the manuscript. N.Z.B.M. provided methodological guidance. H.C. and B.Y. contributed to data collection. Y.S.W. and F.D. revised and refined the manuscript. All authors reviewed and approved the final version of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Ding Fan, Chuan He or Yu Bi.