Heritage Science

RESEARCH

Open Access

Spatial distribution characteristics of Tibetan Buddhism principal-subordinate monastery systems in the Hehuang region

Weijia Li[1,2], Tongtong Liu[1], Huanjie Liu[1*], Yuan Li[3], Shuangying Li[2] and Yue Zhang[2]

Abstract

Tibetan Buddhist monasteries constitute significant cultural heritages of ethnic minorities, evolving into the Principal-Subordinate Monastery System (PSMS) with profound historical and cultural significance. This system exhibits an integrated hierarchical structure in terms of religious dominance, political administration, and cultural diffusion. Existing research primarily focuses on internal humanistic factors such as governance patterns, while there is not any research focused on its patterns and manifestations in spatial distribution. This study aims to elucidate the spatial distribution characteristics of the PSMS in Hehuang region, including the Tibetan Buddhist monasteries from all sects in the Hehuang region since the Song Dynasty It establishes a hierarchical PSMS database based on the affiliation relationships, aimed at storing spatial and property information related to PSMS. The database standardizes the naming and coding of monasteries, and classifies them through hierarchical relationships to ensure data consistency and usability. Finally, the classified and coded monastery data were analyzed by GIS tools to form the PSMS spatial distribution characterisation framework. Results reveal that (1) Monasteries demonstrate notable spatial clustering patterns from both holistic and sectarian perspectives, with density being influenced by the principal monastery's position. (2) Almost every PSMS exhibits a spatial pattern centered around the principal monastery, with subordinate monasteries clustering within a defined range correlated with the administrative region of the principal monastery. (3) PSMS scale variations are controlled by principal monasteries, exhibiting positive correlations in hierarchical structure, control quantity, and distribution range. (4) The spatial orientation of PSMS correlates with river distribution, while the relationships among mountain ranges require further investigation. These findings provide initial insights into the spatial distribution characteristics of PSMS, confirming the spatial influence of the principal monastery. Besides, this study established an innovative spatial research framework for heritage clusters with multiple types and hierarchies. Thus, this study offers new insights into the spatial distribution of Tibetan Buddhist monastery heritage and presents a framework for further examining the spatial distribution of the Tibetan Buddhist monastery heritage in other regions, as well as other heritage clusters where connected and clustered through religious and cultural ties.

Keywords Principal-subordinate monastery systems, Tibetan Buddhism, Spatial distribution, Hehuang region

*Correspondence:
Huanjie Liu
15608067865@163.com
[1] School of Architecture, Tianjin University, Tianjin 300072, China
[2] School of Civil and Transportation Engineering, Qinghai Minzu University, Xining 810007, Qinghai, China
[3] Plateau Provincial Key Laboratory of Energy and Environment, Qinghai Minzu University, Xining 810007, Qinghai, China

Introduction

Tibetan Buddhist monasteries are integral to the cultural heritage of Tibet and its surrounding regions, embodying profound historical lineage, religious beliefs, artistic culture, and educational dissemination [1–3]. These monasteries showcase a rich architectural and artistic culture through diverse material legacies such as architectures [4–6], murals [7, 8], and sculptures [9]. Additionally, they demonstrate deep historical and religious cultural value with their extensive collection of Buddhist scriptures [10] and the hosting of traditional folk activities [11]. Over centuries, these monasteries have witnessed the development of Tibetan cultural traditions and civilization [12], while also embodying unique local ethnic cultural beliefs and characteristics [13], making them highly regarded as precious cultural heritage [14]. Concurrently, as the core of Tibetan society, Tibetan Buddhist monasteries are not only centers for the dissemination of religious beliefs [15] but also vital spaces for community life and education [16, 17], holding important protective significance. However, with the rapid development of urban economies and tourism, Tibetan Buddhist monasteries' heritage faces trends of secularization and commercialization [18]. Furthermore, environmental changes and incomplete historical documentation exacerbate the loss of traditional cultures in cases of building damage and inadequate monastery conservation [19]. These factors collectively present numerous issues and challenges facing the conservation of Tibetan Buddhist monastery heritage, requiring immediate and effective measures for mitigation and protection.

There is a unique cultural phenomenon known as Principal-Subordinate Monastery System (PSMS) in the process of establishing and developing Tibetan Buddhist monasteries [20, 21]. PSMS centers around a principal monastery serving as a political and cultural nucleus, with surrounding subordinate monasteries forming a cohesive network [22]. These subordinate monasteries operate under the governance of the principal monastery, establishing intricate hierarchical relationships and organizational structures within the PSMS [23]. The emergence of this phenomenon coincides with the second diffusion of Buddhism, roughly from the mid-tenth century to the early thirteenth century [22], which led to the diversification of Tibetan Buddhism into sects such as Gelug, Nyingma, Kagyu, Sakya, and Jonang [24, 25], where monasteries played pivotal roles in the propagation and development of these sects [26]. After the initial monastery's construction, surrounding regions would establish smaller monasteries, gradually forming the PSMS network [27]. Within traditional Tibetan Buddhis doctrine, the hierarchical relationships between monasteries are also referred to as mother-son monastery relationships [28–30]. Historical records indicate that during the Ming and Qing dynasties, the Gelug sect established 25 PSMSs in the Qinghai-Tibetan region, encompassing over 300 monasteries [22].

Current research on the PSMS primarily focus on its organizational structure and historical development. La extensively discusses the formation and evolution of the PSMS during the Ming and Qing dynasties, analyzing internal and external factors such as religion, personnel, politics, and economics. He identifies and summarizes various models of the Gelugpa PSMS in Qinghai [22, 24]. Zhu statistically analyzes the spatiotemporal distribution and patterns of Qinghai's principal and subordinate monasteries, briefly addressing the hierarchical characteristics and formation mechanisms of PSMS [21]. Pu has examined relationships of certain PSMS among Tibetan Buddhist monasteries in Qinghai [20]. Additionally, there are some case studies on individual monasteries and their PSMS, such as Seerke Monastery [31], Zhazang Monastery [32], and Kumbum Monastery [33], which investigate the scale, history, and distribution of PSMS. Researchers such as Jie [34] and Shi [27] have also documented aspects of the PSMS within the context of Buddhist historical cultural geography and the symbiotic relationships between monasteries and villages. Moreover, relevant insights into the PSMS have been gleaned from various historical documents, including Tibetan literature [28–30], Chinese historical texts [35], and local county annals [36, 37].

Although Tibetan Buddhist monasteries could be divided into different PSMS by various doctrine and administrations, current research on their spatial distribution mainly focuses on the overall monasteries from the categories of different sects or specific Tibetan regions. Scholars have extensively explored the temporal and spatial distribution characteristics of monasteries from the perspectives of different sects such as Gelugand Sakya. It indicates that the Gelugpa sect shows different spatial distribution patterns in U-Tsang, Amdo, and Kham, reflecting varying degrees of aggregation at different scales. The Gelugpa sect is densely distributed across these Tibetan regions, with the highest density in U-Tsang compared to the other two areas [38 , 39]. In contrast, the Sakya sect is mainly concentrated in the Kham region [40]. Similarly, researchers have investigated the spatial patterns or changes of monasteries in specific Tibetan regions such as Amdo [41], U-Tsang [42], and Kham [40]. Monasteries in Amdo show a distribution pattern of centers in the Gansu-Qinghai area due to historical military support. In contrast, monasteries in U-Tsang cluster in Anterior Tibet and Tsang because of the region's flourishing religious development. Unlike both, monasteries in Kham form multiple high-density centers in the Sichuan region, influenced by the 'Tea Horse Ancient Road' that facilitated cultural and economic exchanges [42].

Recently, there has been increasing attention towards some provinces associated with Tibetan Buddhist monasteries in China. Han's qualitative study of Inner Mongolia, based on historical documentary analysis, revealed that the establishment of monasteries was influenced by factors such as religious policies and the historical significance of the Silk Road [43]. Some scholars utilized geospatial analysis techniques, namely the nearest neighbor index and kernel density estimation, to examine the spatial differentiation characteristics of Buddhist monasteries in Yunnan province. Their results indicate that the distribution of these monasteries is influenced by a multitude of cultural and geo-environmental factors [44]. Notably, research on the distribution of monasteries in Qinghai and the Qinghai-Tibet Plateau has become a focal point. Zhu conducted an in-depth study of Tibetan Buddhist monasteries in Qinghai using the method of literature analysis. It revealed that there were different temporal and spatial distribution characteristics in different periods, such as the Yuan, Song, and Ming dynasties [21]. On this basis, Zhu analyzed the spatiotemporal evolution patterns of Tibetan Buddhist monasteries in Qinghai Province by the mathematical statistics and spatial analysis methods, revealing a "dual-core clustering" spatial distribution with centers in Yushu and Hualong [45]. Xiao also employed GIS tools to examine the spatial distribution characteristics of 66 monasteries in Guoluo Tibetan Autonomous Prefecture in Qinghai Province, and found that these monasteries are mainly located at elevations of 4000–4500 m, showing a close connection with the natural environment [46]. Additionally, Chen has established a historical geographic information database for all Tibetan Buddhist monasteries in the Tibetan area based on the digital humanities approach [47]. It is apparent that the spatial distribution characteristics of Tibetan Buddhist monasteries according to sects and regions have been the attention of the academic community in recent times. Research methodology employed in this field includes historical document analysis and GIS analysis, which provide a methodological foundation for the study of this paper.

However, considering the extensive history and distinctive hierarchical structure of these monasteries, a comprehensive approach to their study and preservation is inadequate. Although there have been studies in the field of humanities that examine the history and structure of PSMS, the unique PSMS specific to Tibetan Buddhism has rarely been utilized as a categorization framework in previous spatial distribution research. As a result, there is a dearth of systematic and orderly investigations into the spatial distribution characteristics of monasteries from the PSMS perspective. Accordingly, the core research question of this study is defined as follows: what are the spatial distribution patterns and characteristics of Tibetan Buddhist PSMS? This study aims to classify monasteries into different types of PSMS, according to different doctrines and management systems, and to conduct detailed analyses from the following perspectives: spatial hierarchy and quantity scale, spatial clustering and distance range, as well as spatial center and cardinal direction, so as to elucidate more accurately the distributional characteristics of Tibetan Buddhist monasteries and to provide a scientific basis for the protection and preservation of Tibetan Buddhist monasteries.

Therefore, this study focuses on all Tibetan Buddhist monasteries in the Hehuang region since the Song Dynasty by collecting data from historical documents, field investigations, and the religious lists published by the State Administration of Religious Affairs of China. Initially, the hierarchical structure of the monasteries is clarified based on the classification of primary and subsidiary monasteries, and a GIS-based monastic heritage database is established. Subsequently, a spatial research framework of data classification and coding with various GIS analysis tools is used to summarize the distribution characteristics of Tibetan Buddhist monasteries, both from a holistic perspective and within each system. This framework analyzes the spatial pattern of the PSMS through its spatial hierarchical structure, aggregation features, and main center; examines the spatial scale based on the hierarchical structure, number of monasteries, and distribution range; and explores the distribution direction concerning its relationship with nature. Finally, the factors influencing the formation and scale of this spatial pattern are explored.

This approach corroborates the dominant role of principal monasteries in cultural and geographical contexts, introduces a novel classification basis for Tibetan Buddhist monastic heritage, and lays a analysis foundation for future research on the spatial distribution and conservation of heritage cluster that is diverse and multi-leveled, connected by religious and cultural ties. In addition, the protection of Tibetan Buddhist monasteries regarded as PSMS is of paramount importance from a practical perspective. The establishment of the PSMS will not only guarantee the integrity of monastic heritage conservation, but also prevent the fragmentation of cultural ties caused by unquestioning and uncritical conversation. Furthermore, it will determine the priority of protection and resource allocation according to the scale and influence of the monasteries in the system. Concurrently, it could also provide a basis for the classification of categories of Tibetan Buddhist cultural areas, so as to plan and design tourism routes in a more rational manner, and to protect by community participation from promoting the community's sense of identity with the heritage.

Study area overview

The Hehuang region, located in the northeastern part of Qinghai Province, China, is a unit of natural geographic division. Its geographical position is shaped by the river valleys formed by the confluence of the Yellow River, Huangshui River, and Datong River [48]. According to the definition by the 1989 comprehensive survey team of the Chinese Academy of Sciences on the Loess Plateau, the Hehuang region includes counties and cities such as Xining, Huangyuan, Huangzhong, Datong, Huzhu, Ping'an, Ledu, Minhe, Xunhua, Hualong, Tongren, Jianzha, Guide, and Menyuan, covering a total area of approximately 36,000 square kilometers [49].

As a core area of Tibetan Buddhism culture, the Hehuang region has a large Tibetan population, a long history of Tibetan Buddhist development, and a rich Tibetan cultural heritage [50]. The region is densely populated with Tibetan Buddhist monasteries, making it one of the areas with the highest concentration of such monasteries [44]. The Hehuang region serves as an important transportation hub on the ancient Tang-Tibet Road and the southern section of the Silk Road [51, 52], and is considered a sacred site for the "lower route transmission" during the later propagation of Tibetan Buddhism [53]. This has played a crucial role in the distribution and development of monasteries, facilitating not only the flow of material goods but also enhancing cultural exchanges. Monasteries are often distributed along these major transportation routes, facilitating pilgrimages and interactions among monks, while also aiding in securing more funding and support for the monasteries. Furthermore, the Hehuang region is the birthplace of Tsongkhapa, the founder of the Gelug sect [54], and includes multiple sects such as Gelug and Nyingma, forming diverse PSMS in the process of doctrinal transmission and cultural dissemination [22].

The natural environmental characteristics of the Hehuang region have significantly influenced the spatial distribution and historical development of Tibetan Buddhist monasteries. This area is not only the intersection of the Qinghai-Tibet Plateau and the Loess Plateau but also features a complex topography with interwoven mountains, valleys, and basins, creating a unique mixed agricultural and pastoral production method [55]. Such complex terrain and diverse production methods provide various options for monastery site selection. Some monasteries are located in relatively flat and easily accessible areas, such as river valleys, while others are built on mountains, utilizing the terrain to enhance their grandeur and mystery [56]. Additionally, climatic conditions have a significant impact on the siting and distribution of monasteries in the Hehuang region, characterized by high altitude and arid climate [57]. The scarcity of water resources necessitates that monastery sites prioritize proximity to water sources. Monasteries typically choose locations near rivers, springs, or areas with abundant groundwater to ensure the water needs for daily life and religious activities are met [22]. Therefore, the natural environmental characteristics of the Hehuang region are closely linked to the spatial distribution and historical development of Tibetan Buddhist monasteries. Factors such as topography, climate, and transportation routes collectively shape the distribution pattern and historical evolution of monasteries in this region [58] (Fig. 1).

Materials and methods

Data collection

The data for this study on Tibetan Buddhist monasteries was primarily collected by three methods. Firstly, primary data on monasteries is obtained from local chronicles, archival documents, and historical literature of the Hehuang region. Some specialized monographs and scholarly journal articles detailing monasteries are also reviewed to gather additional information related to monasteries. Secondly, data is supplemented and verified using publicly accessible resources from official websites such as the National Religious Affairs Administration in China (https://www.sara.gov.cn/resource/common/zjjcxxcxxt/) to ensure data accuracy. Finally, field surveys are conducted to address potential gaps and errors in historical records, correcting monastery address discrepancies and enriching monastery data with detailed background information obtained through interviews with local residents. In addition, the elevation data comes from the DEM elevation data published by the Chinese Academy of Sciences' Computer Network Information Center (http://www.gscloud.cn); the hydrological data comes from the Chinese Geographic Information Resource Directory Service System (https://www.webmap.cn).

Through these systematic procedures, a comprehensive database of Tibetan Buddhist monastic heritage in the Hehuang region is compiled. This database mainly records information about 389 monasteries, including geographic locations, affiliated sects, PSMS information, time of establishment and demolition, architectural style, scale, and resident lamas. Following a thorough selection process, 105 independent monasteries lacking definitive PSMS information were excluded, along with 25 monasteries possessing PSMS affiliation but belonging to systems with fewer than 4 monasteries in the Hehuang region. Ultimately, a total of 259 monasteries with clear primary affiliations and at least 4 monasteries within their respective systems in the Hehuang region have been identified as the subjects of analysis.

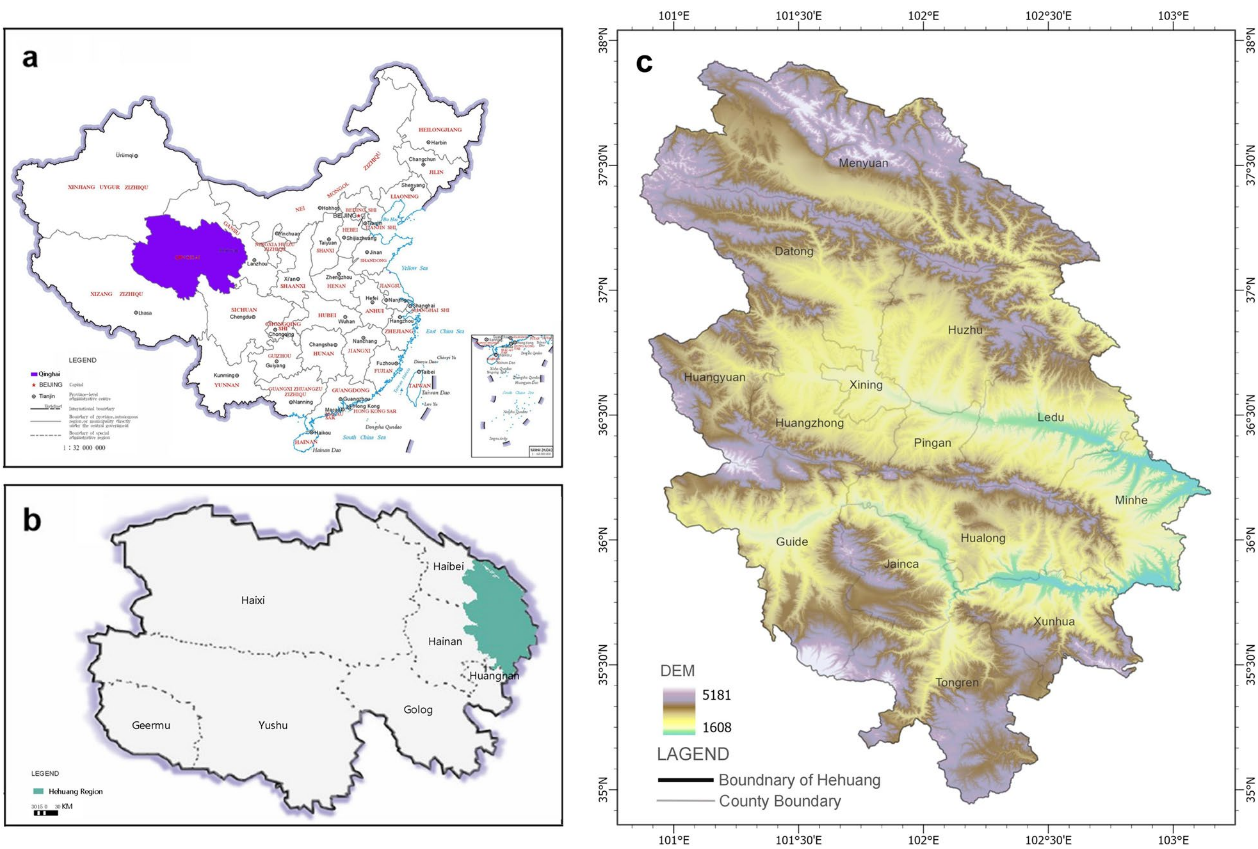


Fig. 1 The location of the research area. **a** China Area; **b** Qinghai Province Area; **c** Hehuang Region

Type classification

In contrast to other subjective hierarchical classifications of Tibetan Buddhist monasteries, this study utilizes a classification based on established hierarchies and rules within the PSMS of Tibetan Buddhism, which have been academically validated [21, 23, 27]. Specifically, this study initially categorizes all monasteries in the Hehuang region into various sects such as Nyingma, Sakya, Kagyu, Kadam, and Gelug based on sectarian differences. Subsequently, considering variations in sect lineages, doctrinal systems, and the channels through which monks study scriptures, monasteries are further distinguished into principal (main) and subordinate (branch) monasteries. La has defined the PSMS consisting solely of principal and subordinate monasteries as a two-tier structure model [22]. Moreover, if subordinate monasteries govern other monasteries, leading to more complex hierarchical relationships, this PSMS is termed as a multi-tier structure model [22].

Drawing from this classification, this study categorizes the Hehuang region's PSMS into two-tier structure models and multi-tier structure models (e.g., three-tier, four-tier) as depicted in Fig. 2. Additionally, monasteries in the Hehuang region are coded for research convenience. Table 1 illustrates the coding scheme for principal and select subordinate monasteries, with Longhe Monastery and its subordinate Lianhuatai Monastery serving as an example. It should be noted that monasteries that have changed sect affiliations over time are classified based on their current sect affiliation, due to the absence of spatiotemporal evolution analysis.

Analysis tools

The study utilizes GIS spatial analysis tools to investigate monastery spatial distribution patterns from holistic, sectarian, and PSMS perspectives, respectively. Specifically, the analysis involves the following approaches (Fig. 3 and Table 2): (1) Exploring aggregation characteristics and clustered areas of monasteries from overall and sectarian perspectives using methods such as Average nearest neighbor and Kernel density estimate. (2) Investigating clustering characteristics of the PSMS through Average nearest neighbor analysis, and analyzing spatial scale characteristics of PSMS using buffer analysis. (3) Utilizing techniques such as centroid summarization, Standard deviation ellipses, and proximity analysis to examine

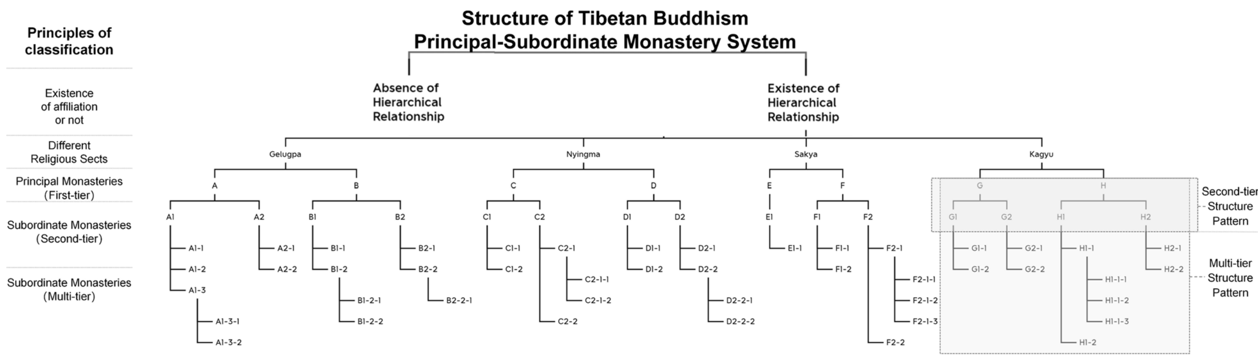


Fig. 2 Structure of Tibetan Buddhism Principal-Subordinate Monastery System

Table 1 Codes for all principal and subordinate monasteries

Principal monastery	Codes	Second-tier Subordinate Monasteries (Longhe Monastery)	Codes	Multi-tier Subordinate Monasteries (Lianhuatai Monastery)	Codes
Caidan Monastery	A	ZhaChu Monastery	E1	Hanjia Monastery	E6-1
Deqian Monastery	B	Hongshan Monastery	E2	Gangou Monastery	E6-2
Gulei Monastery	C	Jiakanjo Monastery	E3	Guangjiao Monastery	E6-3
Guanghui Monastery	D	Kajiji Monastery	E4	Guangji Monastery	E6-4
Longhe Monastery	E	MuangLa Monastery	E5	Guanglong Monastery	E6-5
Longwu Monastery	F	Lianhuatai Monastery	E6	Hullijia Monastery	E6-6
Qutan Monastery	G	Puhua Monastery	E7	LiJia Monastery	E6-7
Kumbum monastery	H	Chazang Monastery	E8	Pine Monastery	E6-8
Wendu Monastery	I	Sanjia Monastery	E9	Tuanjie Monastery	E6-9
Yuning Monastery	J	Shanfo Monastery	E10	Hendang Monastery	E6-10
ZhiHajia Monastery	K	Zhangjia Monastery	E11	Zengfu Monastery	E6-11
Banzhuwa Monastery	L	Zhaojia Monastery	E12	Zhuangzigou Monastery	E6-12

the spatial centroids and orientations of different PSMS. Finally, the univariate chi-square test is employed a to furthering verify the correlation between PSMS distributions and environmental factors.

Results

Spatial distribution characteristics of all monasteries

Distribution characteristic from the holistic perspective

A comprehensive study of the distribution patterns of all Tibetan Buddhist monasteries in the Hehuang region is conducted initially. To better display the density trends within the study area of the Hehuang region, we ultimately chose 20 km as the bandwidth. Figure 4a presents the Kernel density estimate results for monasteries in the Hehuang region, showing a prominent clustering tendency through visualization. This observation is corroborated by the Average nearest neighbor with a z-score of -4.787, indicating a statistically significant inclination towards spatial clustering of monasteries. The negative z-score indicates a significant spatial clustering tendency of the monasteries, with larger absolute values of the z-score representing a higher degree of deviation from a random distribution. Furthermore, the associated p-value, which measures the probability that the observed clustering pattern is due to random chance, is very low (typically $p < 0.05$ for significance). This low p-value confirms that the clustering is not random but statistically significant, further validating the clustering observed in the Kernel density estimate.

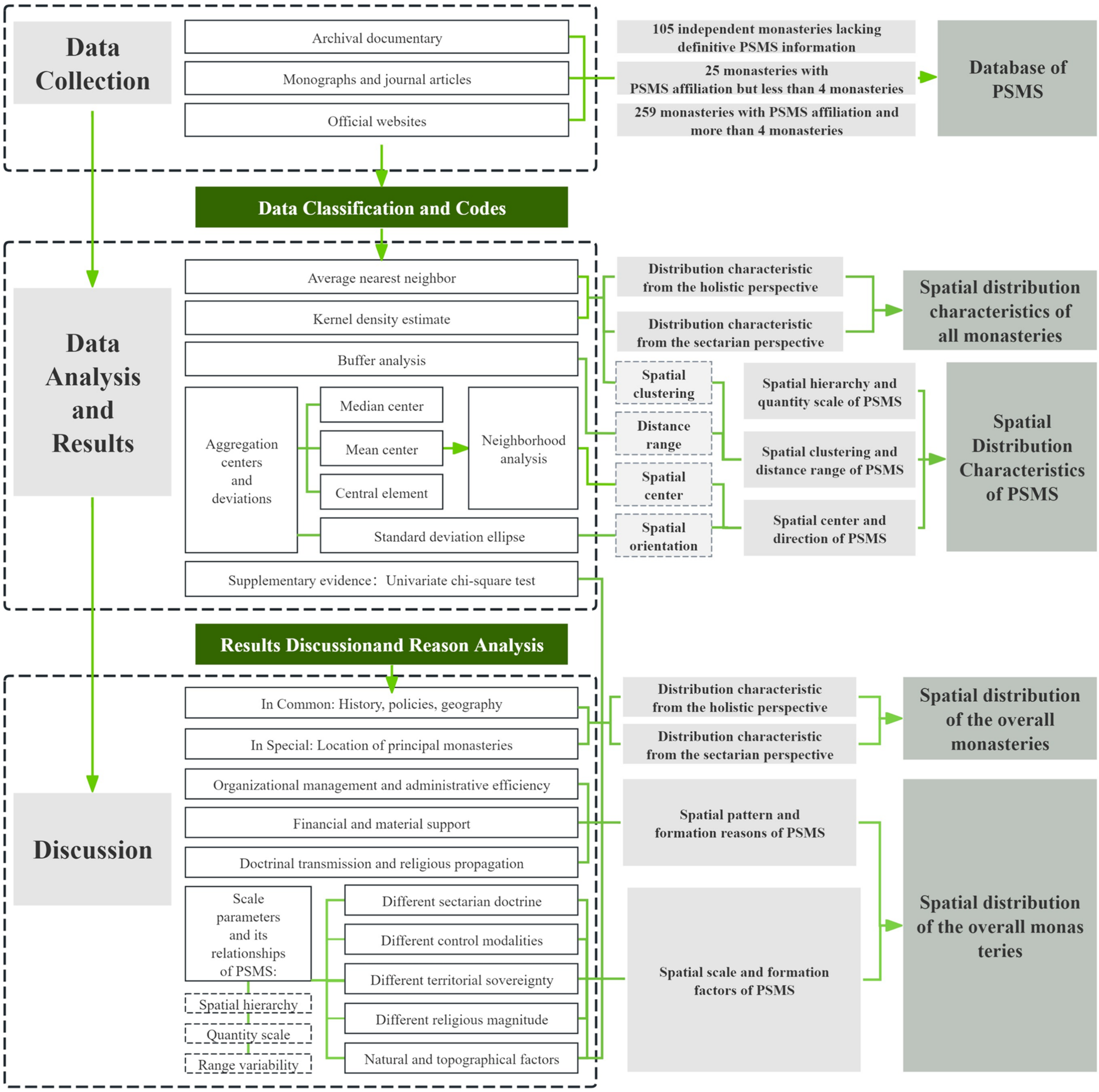


Fig. 3 Framework for researching Tibetan Buddhism PSMS

Furthermore, Fig. 4a highlights notable regional disparities in monastery density. High-density areas are primarily concentrated in the eastern and southern Hehuang region, while density gradually decreases in the central and western parts, with the northern area having relatively few monasteries. Specifically, regions such as the border between Hualong and Minhe, northern Tongren, northern Huangzhong, northwestern Hualong, and both eastern and western Xunhua, as well as central Guide, exhibit high monastery densities, with values of Kernel density estimates exceeding 0.020. Areas such as eastern Jianzha, northern Ledu, and central Huzhu exhibit secondary high-density characteristics, with Kernel density estimate values exceeding 0.011. In contrast, regions such as Datong, Menyuan, Huangyuan, Xining, and Ping'an have lower monastery densities, with Kernel density estimate values below 0.006. In summary, the distribution of monasteries in the Hehuang region exhibits observed regional variation. Higher clustering is observed in the

Table 2 GIS spatial analysis tools for researching Tibetan Buddhism PSMS

Method name	Basic principle	Application scenario	Usage in this study	Citation
Average Nearest Neighbor	Calculates the average distance from each spatial feature to its nearest neighbor	Spatial distribution pattern analysis	Used to identify spatial clustering patterns of monasteries in the Hehuang region, considering all monasteries, monasteries from different sects, and monasteries within different PSMS	[59, 60]
Kernel Density Estimate	Estimates the distribution density of a feature in space	Hotspot identification, resource distribution studies	Utilized to explore spatial clustering areas from both a holistic perspective and within different sects. By calculating monastery density within each geographic grid unit, density heatmaps are generated to visually showcase areas of monastery concentration, sparsity, as well as potential diffusion or clustering patterns	[61–64]
Aggregation Centers and Deviations	Describes the distribution direction and range of spatial data	Spatial distribution characteristic analysis	Utilized to investigate the spatial centers of PSMS and their spatial distribution orientations, thereby providing spatial quantification data support for the influence centers and directions of these systems	[65–70]
Neighborhood Analysis	Analyzes other features in the vicinity of a specific spatial feature	Proximity analysis, spatial relationship studies	Used to verify the coincidence and correlation between the mean centers identified in the above steps and the principal monasteries of their respective PSMS. Through nearest neighbor analysis, the closest principal monastery to the mean center of each PSMS was identified, and the spatial distance between these points was measured	[71, 72]
Buffer Analysis	Establishes a buffer zone of fixed distance around a geographic entity	Influence range analysis, proximity issues	Used to determine the spatial distribution range of each PSMS under the influence of the principal monasteries. This method quantifies and validates the extent and intensity of influence exerted by each system	[73, 74]
Univariate chi-square test	Compare the observed frequencies in categorical data to the expected frequencies under a specific hypothesis	Testing observed vs. expected frequencies	Used to examine the correlation between the spatial distribution of PSMS and natural influencing factors such as elevation and hydrology	[75, 76]

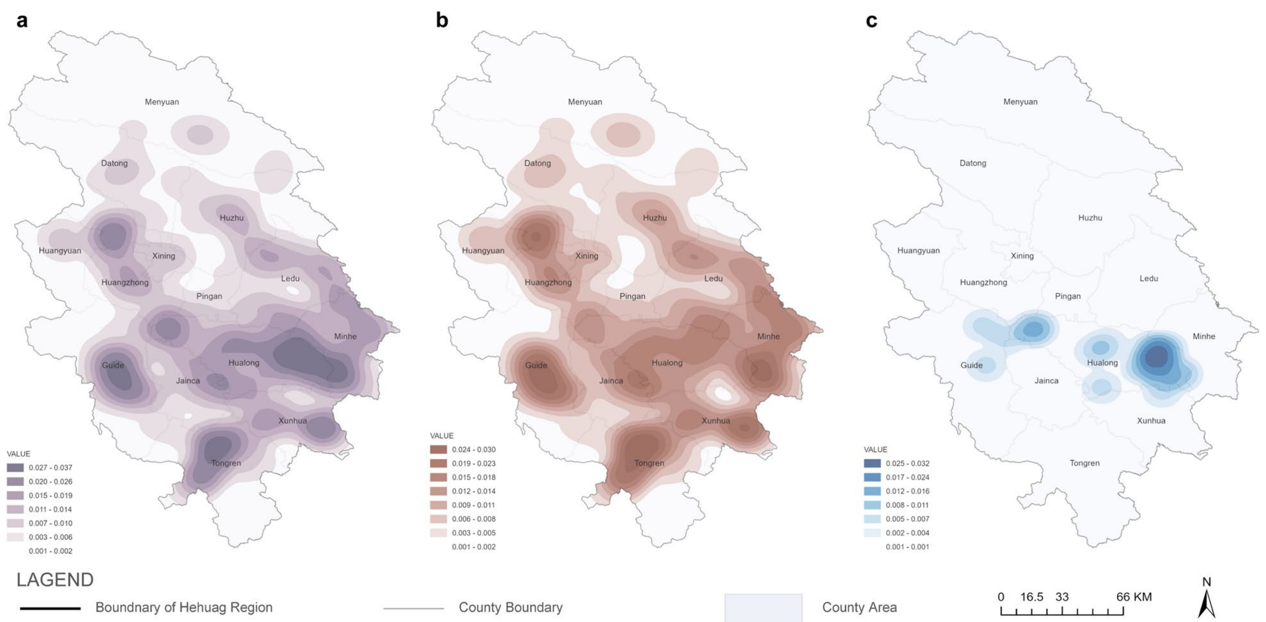


Fig. 4 Holistic kernel density distribution of monasteries. **a** All principal and subordinate monasteries; **b** Gelug's Monasteries; **c** Nyingma's Monasteries

eastern and southern areas, while the western and northern areas show relatively lower clustering.

Distribution characteristic from the sectarian perspective

Average nearest neighbor analysis and Kernel density estimate are also utilized to further investigate the spatial distribution of monasteries across different Tibetan Buddhism sects. The existing monasteries in the Hehuang region currently belong to Gelug and Nyingma sects and lack representation from other sects. Monasteries of the Gelug and Nyingma sects, with z-scores of -4.361 and -5.721 respectively (as shown in Table 3), indicating significant clustering tendencies for both sects. However, the degree of clustering differs between them, with Nyingma monasteries exhibiting a higher level of clustering compared to Gelugpa monasteries, as indicated by the lower z-score.

By comparison, the spatial distribution patterns of monasteries from different sects exhibit significant differences. Specifically, the density distribution characteristic of Gelugpa monasteries (Fig. 4b) closely resembles the overall distribution characteristic of monasteries (Fig. 4a), indicating an extensive spatial distribution in the Hehuang region. Conversely, Nyingma monasteries demonstrate a pronounced spatial clustering tendency (with a KDM value of 0.012), predominantly situated at the junction of Hualong and Guide, as well as in the eastern part of Hualong (Fig. 4c). These distinctions suggest that the spatial distribution patterns of monasteries in the Hehuang region exhibit significant variation by the different sect.

Spatial distribution characteristics of PSMS

This study aims to investigate the spatial representation of organizational structures and management

Table 3 Nearest Neighbor Index result for all monasteries

Type	R	Average nearest neighbor distance (km)	Expected nearest neighbor distance (km)	z score	p value	Distribution pattern
Overall PSMS	0.845	4.9	5.8	−4.787	0.000	Significantly clustered
Gelugs's Monasteries	0.851	5.2	6.1	−4.361	0.000	Significantly clustered
Nyingmas's Monasteries	0.376	7.4	19.6	−5.721	0.000	Significantly clustered

characteristics across different PSMS by examining the distribution patterns and scale of each system in relation to hierarchy and quantity, as well as clustering and range. Additionally, this study further substantiates the central role of principal monasteries in governance and religious culture by identifying their geographical centrality. Moreover, the research explores potential distribution orientations of each system under the control of principal monasteries, aiming to achieve a more comprehensive understanding of the complexity and diversity of PSMS under the influence of various cultural and natural factors.

Spatial hierarchy and quantity scale of PSMS

The organizational hierarchy and structures of PSMS in the Hehuang region are clearly delineated on maps illustrating spatial relationships (Fig. 5) and visual charts depicting affiliation relationships (Fig. 6). In general, these representations encompass 12 PSMS which are affiliated with the Gelug and Nyingma sects. Among these, the Gelug-affiliated systems predominate, including 10 principal-subordinate systems such as Caidan, Deqian, Gulei, Guanghui, Longhe, Longwu, Qutan, Kumbum, Wendu, and Yuning. In contrast, the number of Nyingma-affiliated monasteries is relatively small, with only two principal-subordinate systems, namely ZhiHajia and Banzhuwa.

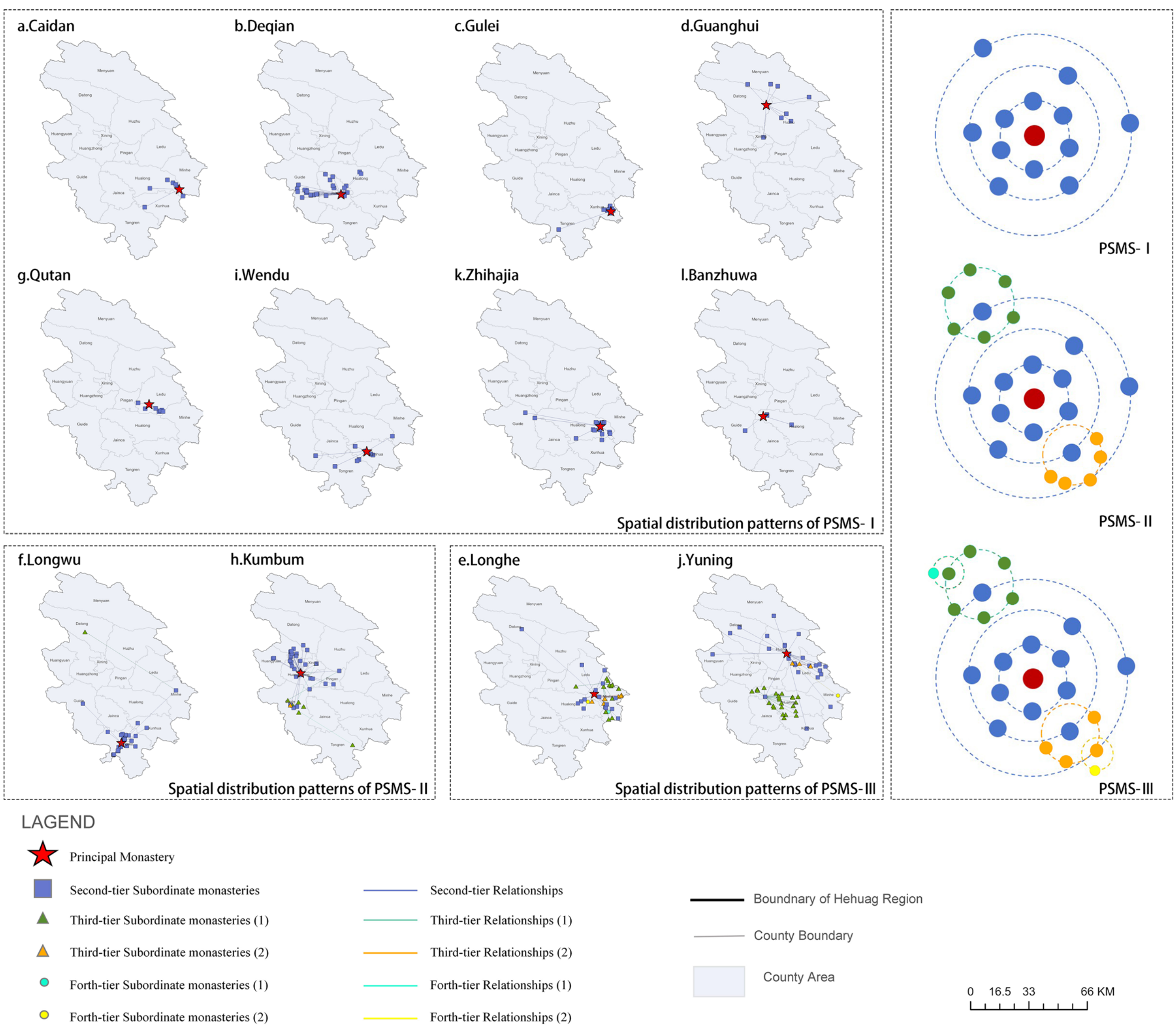


Fig. 5 The spatial hierarchical distribution pattern of PSMS

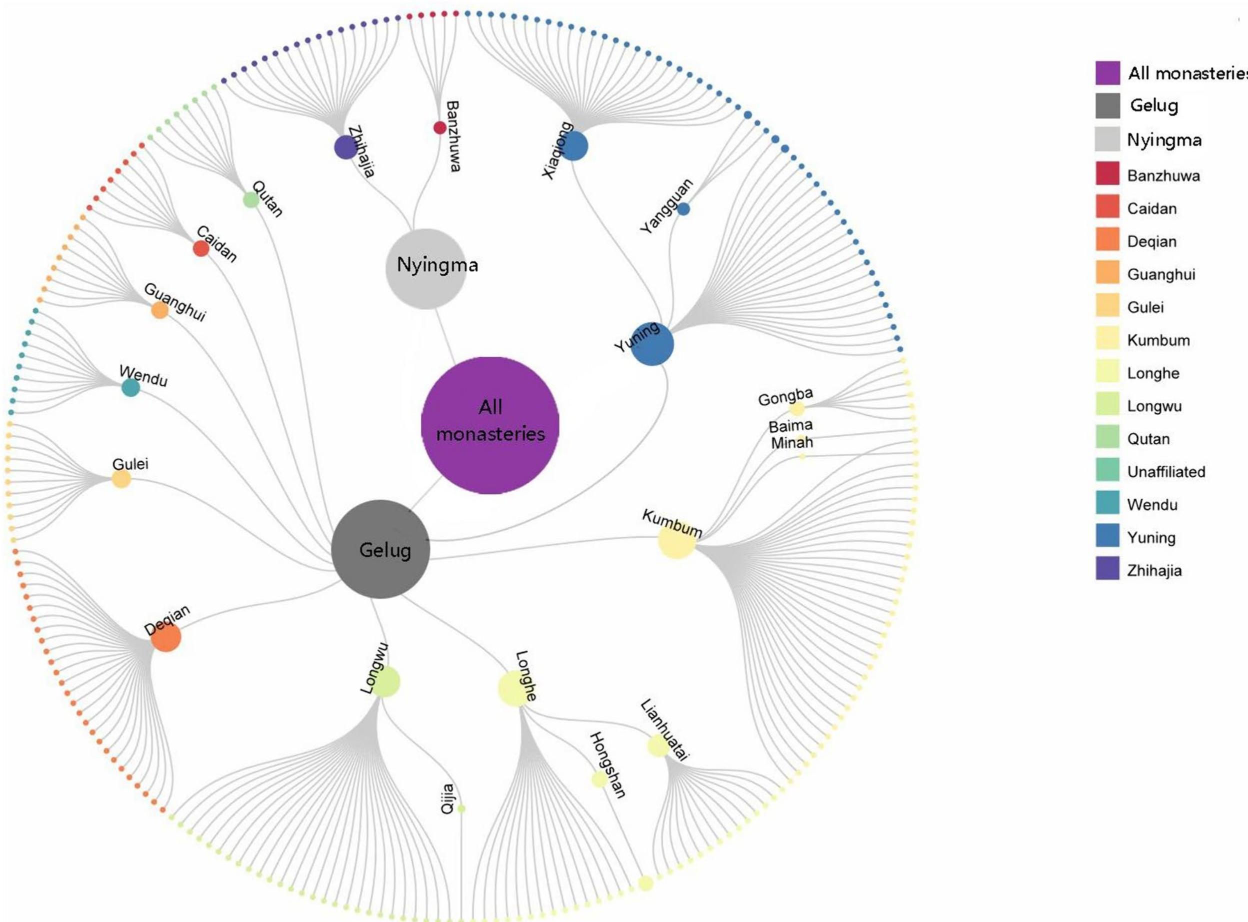


Fig. 6 The hierarchy and structure of PSMS in Hehuang Region

According to Fig. 5, the spatial distribution of these 12 PSMSs is analyzed and the spatial hierarchical patterns of PSMSs are summarized and classified into three categories, from the tightly connected PSMS-I level to the more dispersed PSMS-II level, and finally to the widely spread PSMS-III level. This spatial hierarchical pattern provides valuable insights into the organizational structure and diffusion of religious influence among Tibetan Buddhist monasteries in geospatial terms.

Spatial hierarchical pattern of PSMS-I

The PSMS-I demonstrates the core spatial relationships between a principal monastery (represented in red) and its directly associated second-tier subordinate monasteries (represented in blue). These spatial relationships are characterized by a high degree of concentration, where the principal monastery forms a tight network with its second-tier subordinate monasteries in the surrounding area. The system A, B, C, G, I, H, and L exemplify this hierarchical model, where second-tier subordinate monasteries are clustered around the principal monastery, forming a clear "core-periphery" structure. This model indicates that the principal monastery exerts strong spatial control and influence over its associated second-tier subordinate monasteries, which are typically located within a relatively close geographic range.

Spatial hierarchical pattern of PSMS-II

The PSMS-II represents secondary spatial relationships, involving third-tier subordinate monasteries (represented in green or orange) that are connected to the second-tier subordinate monasteries. The spatial relationships in this level are more dispersed compared to PSMS-I but still maintain a distinct hierarchical structure. For instance, the system F and H illustrate the PSMS-II model, where third-tier subordinate monasteries are spread across a broader geographical region and are spatially connected to the core monastic network. This model reflects the role of second-tier subordinate monasteries in extending the religious and cultural network over a wider area.

Spatial hierarchical pattern of PSMS-III

The PSMS-III involves the spatial relationships among fourth-tier subordinate monasteries (represented in light green and yellow), typically located in remote areas. The spatial connections at this level are the most dispersed, covering a wide area with long-distance connections. The system E and J show that fourth-tier subordinate monasteries are distributed in more remote regions, with relatively loose spatial connections between them. Despite the wide distribution, these monasteries maintain a basic religious network structure. This model emphasizes the peripheral diffusion of religious influence across geographical space.

Subsequently, all monasteries are systematically coded and quantified according to their hierarchical relationships, and visually represented in Fig. 7. The innermost circle illustrates three types of monasteries in the Hehuang region: 105 independent monasteries without PSMS information, 25 monasteries affiliated with PSMS whose systems with fewer than 4 monasteries in the region, and 259 monasteries affiliated with PSMS and having at least 4 monasteries within their system in the region. The second circle highlights 259 monasteries within PSMS, with Gelug monasteries representing 92% and Nyingma monasteries 8%. The third circle details the number of monasteries within 12 systems, showing prominent variation. Among Gelug systems, System J owns the largest number of monasteries (21%), followed by E (15%) and H (16%). Systems B and F account for approximately 10%, while systems A, C, D, G, and I are smaller, ranging from 3 to 4%. Nyingma systems K and L are much smaller, at 7% and 2%. The fourth and fifth circles represent the number of secondary and multi-tier structural patterns, with Systems E, F, H, and J displaying multi-tiered structures. Notably, Systems E and J have extensive subordinate monasteries, each with four-tier hierarchies.

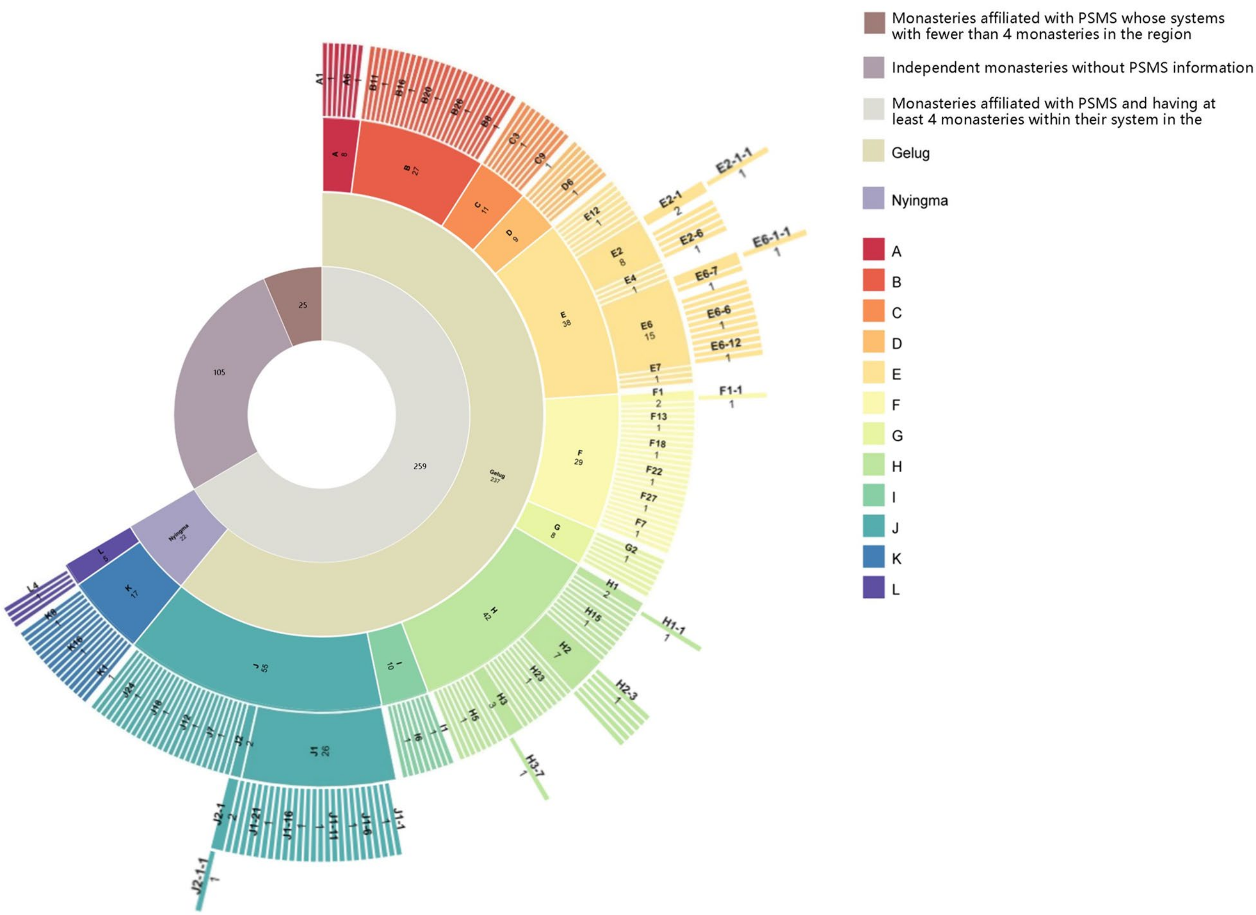


Fig. 7 Number of hierarchy and structure of PSMS in Hehuang Region

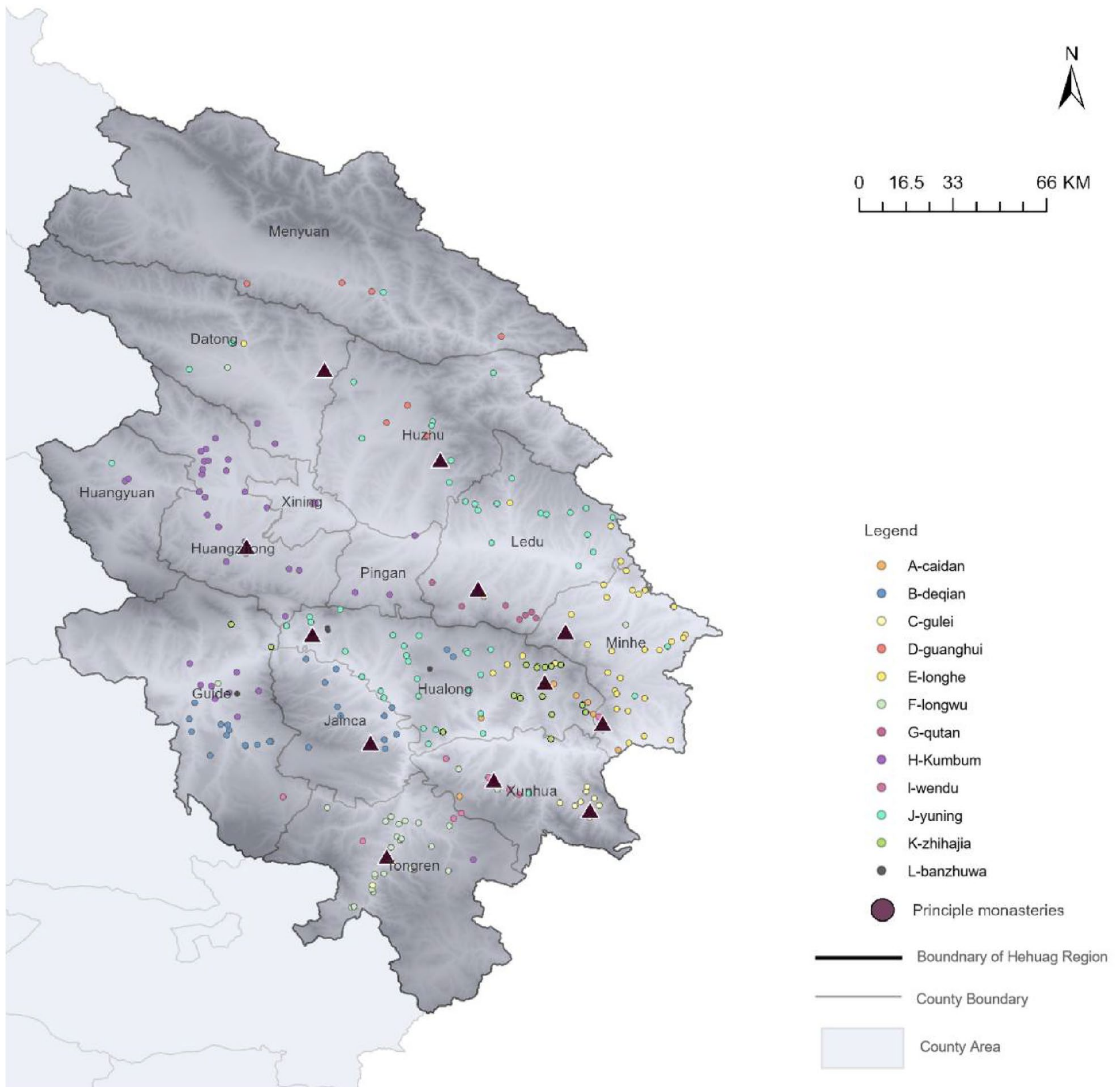


Fig. 8 Spatial distribution of PSMS in Hehuang Region

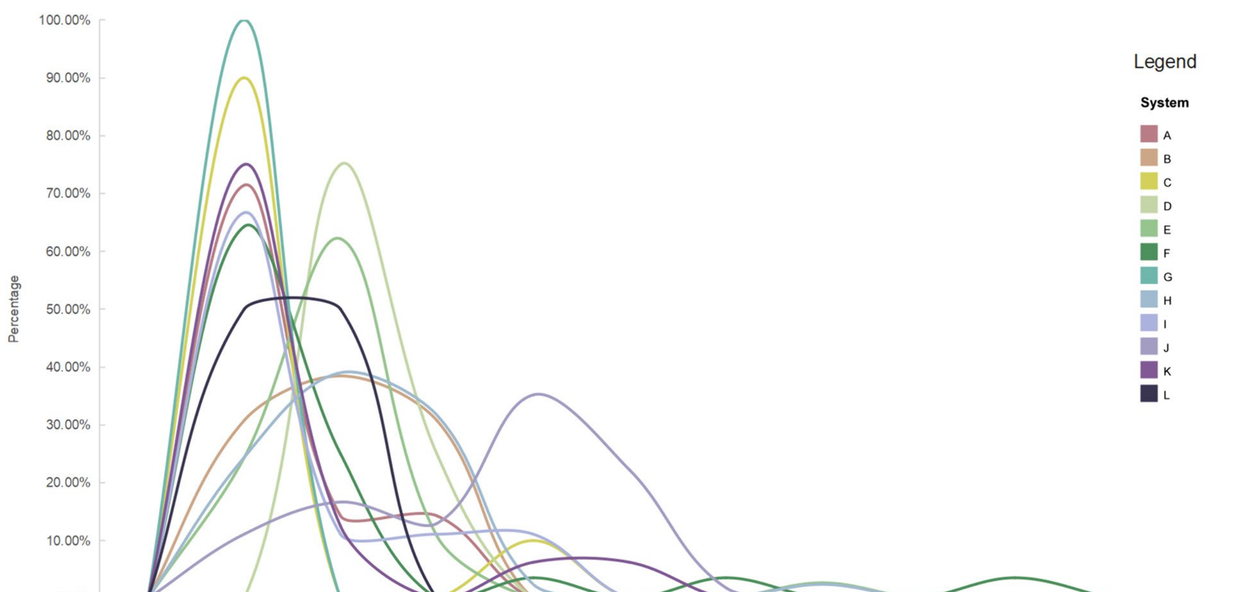
Spatial clustering and distance range of PSMS

Figure 8 illustrates the spatial distribution for each PSMS. To further investigate the spatial clustering or dispersion of these systems, the Average nearest neighbor analysis is first employed to quantitatively verify the clustering tendency within each PSMS. The results indicate that all the systems exhibit significant or moderate clustering, as illustrated in Table 4. This suggests that the layout of monasteries within each PSMS generally tends to cluster. Besides, Fig. 8 displays the spatial distribution of principal monasteries. According to the results in Table 4, the layout pattern of the principal monasteries shows a significant dispersion (z-score of 3.537), indicating that there is no evident clustering effect among them.

Secondly, buffer analysis was utilized to further validate the spatial clustering of PSMS and to precisely quantify their clustering range. Given the maximum distance of nearly 18 km between the farthest subordinate monastery and the principal monastery, this distance was divided into nine intervals of 20 km each. Regarding the principal monastery as the center, monastery counts were tallied within each 20-km radius interval.

Table 4 Nearest Neighbor Index result for all PSMS

Type	R	Average nearest neighbor distance (km)	Expected nearest neighbor distance (km)	z score	p value	Distribution pattern
All principal monasteries	1.534	41.6	27.1	3.537	0.000	Significantly dispersed
A	0.424	14.1	33.2	−3.114	0.002	Significantly clustered
B	0.263	4.7	18.1	−7.330	0.000	Significantly clustered
C	0.359	10.2	28.3	−4.064	0.000	Significantly clustered
D	0.792	24.8	31.3	−2.279	0.023	Moderately clustered
E	0.680	10.4	15.2	−3.770	0.000	Significantly clustered
F	0.814	14.2	17.4	−1.919	0.055	Less strongly clustered
G	0.218	7.2	33.2	−4.234	0.000	Significantly clustered
H	0.593	8.6	14.5	−5.042	0.000	Significantly clustered
I	0.543	16.1	29.7	−2.765	0.006	Significantly clustered
J	0.800	10.1	12.7	−2.837	0.005	Significantly clustered
K	0.315	7.2	22.8	−5.402	0.000	Significantly clustered
L	0.439	18.4	42.0	−2.400	0.016	Moderately clustered



	0	0-20	20-40	40-60	60-80	80-100	100-120	120-140	140-160	160-180	Over 180	Range variability
A		71%	14%	14%								44.7
B		31%	38%	31%								48.2
C		90%			10%							65.6
D			75%	25%								25.2
E		24%	62%	11%				3%				129.5
F		64%	25%		4%		4%			4%		173.6
G		100%										11.5
H		24%	39%	32%	2%			2%				126.6
I		67%	11%	11%	11%							58.9
J		11%	17%	13%	35%	22%	2%					116.8
K		75%	13%		6%	6%						89.5
L		50%	50%									31.1

Fig. 9 Distance range of the PSMS in Region

The results shown in Fig. 9 reveal a pronounced concentration of monasteries within a 20km radius of principal monasteries for each PSMS. Notably, all monasteries within System G are within this range. Systems C, A, and K also have high densities, comprising 90%, 71%, and 75% of their total monasteries, respectively. When the distance extends to 40 kms, Systems B, D, E, H, and L show a notable increase in the number of monasteries, with System L containing all its monasteries within this range. Within a 60-km radius, almost all systems include more than 88% of their monasteries except for System J, while System J reaches its peak monastery count within the 60 to 80-km range. Beyond 80 km, the number of monasteries decreases in all systems, with only a few systems having monasteries located beyond 100 km, specifically E, F, H, and J. In summary, most PSMS in the Hehuang region exhibit pronounced spatial clustering, with over 88% of monasteries located within a 60-km radius of their principal monasteries.

Subsequently, to further delineate the range characteristics of each system, the variability in the spatial distribution range within the principal-subordinate monastery systems is indicated by the difference between the maximum and minimum distances from the subordinate monasteries to the principal monasteries.. This range variability is visually represented in Fig. 9, where a broader span on the x-axis corresponds to a wider distribution range. The results reveal that Systems F, E, and J exhibit the widest distribution ranges, with difference values of 173.6km, 129.5km, and 116.8km, respectively. In contrast, Systems G, D, and L demonstrate comparatively narrower distribution ranges, with difference values of 11.5km, 25.2km, and 31.1km, respectively. The distribution ranges of the other systems fall between these extremes, illustrating varying degrees of distribution range.

Spatial center and cardinal direction of PSMS

The spatial dominance center of PSMS was analyzed using the method of aggregation centers and deviations, with the weighting field defined as the number of subordinate monasteries. The outcomes are illustrated in Fig. 10, showing the central element, median center, mean center, and Standard deviation ellipse. It is evident that the central element of each PSMS aligns with its principal monastery. Furthermore, except for System J, most median centers of PSMS predominantly coincide with the position of their principal monasteries. Additionally, while the mean centers exhibit slight disparities from the principal monastery positions, they are geographically close as they largely remain within the confines of the same county, within a specific distance. It could be proven by neighborhood analysis (Table 5) which illustrates that the neighboring elements of mean centers correspond to the principal monasteries of their respective systems, with distances seldom exceeding 11 km, except for System J. The reason for this deviation is that one of the second-tier monasteries in system J has a large number of third-tier monasteries, and they are geographically distant from the original principal monastery, over 60 km away. In summary, the spatial centers of most PSMS closely approximate the locations of their principal monasteries, thereby establishing a spatial distribution pattern centered around these principal monasteries.

Simultaneously, the results of the Standard deviation ellipses, which indicate the distribution orientation of each PSMS, are presented in Fig. 10. It is evident that the distribution orientations of various systems exhibit diversity alongside the distribution of water systems, such as Yellow River and its tributaries, the Hehuang River and Datong River. System D is located to the north of the Hehuang River and follows the direction of the Datong River, while Systems H, J, and E are intersected by the Hehuang River, distributing perpendicular to its flow direction on both sides. Systems A, K, and L are located to the north of the Yellow River, showing a consistent orientation aligned with the direction of Yellow River. Similarly, Systems B, I, and C are located to the south of the Yellow River and in close proximity to it, showing a resemblance in orientation of the Yellow River. System F is distributed along both sides of the Longwu River, a secondary river of the Yellow River. However, Systems G and those situated farther from the rivers show no distinct correlation.

Discussion

Spatial distribution of the overall monasteries

In general, the monasteries in the Hehuang region exhibit a distinct clustering tendency, primarily influenced by historical accumulation, governmental policies, and geographical location. Historically, since the mid-ninth century AD, Tibetan Buddhist monks, known as the "Three Wise Men," fled to Qinghai due to the prohibition of Buddhism in Tibet. This facilitated the dissemination and development of Tibetan Buddhism in the region [43]. Scholars have documented that monasteries such as Xiongxian Monastery, Dandou Monastery, and Zhazang Monastery in locations like Hualong and Huangyuan were constructed before the Song Dynasty [21]. From then on, the Hehuang region also became a crucial center for the dissemination of Tibetan Buddhist culture, with many Tibetan Buddhist monasteries being built successively.

The government policies of the Ming and Qing dynasties also played a crucial role in the concentration of

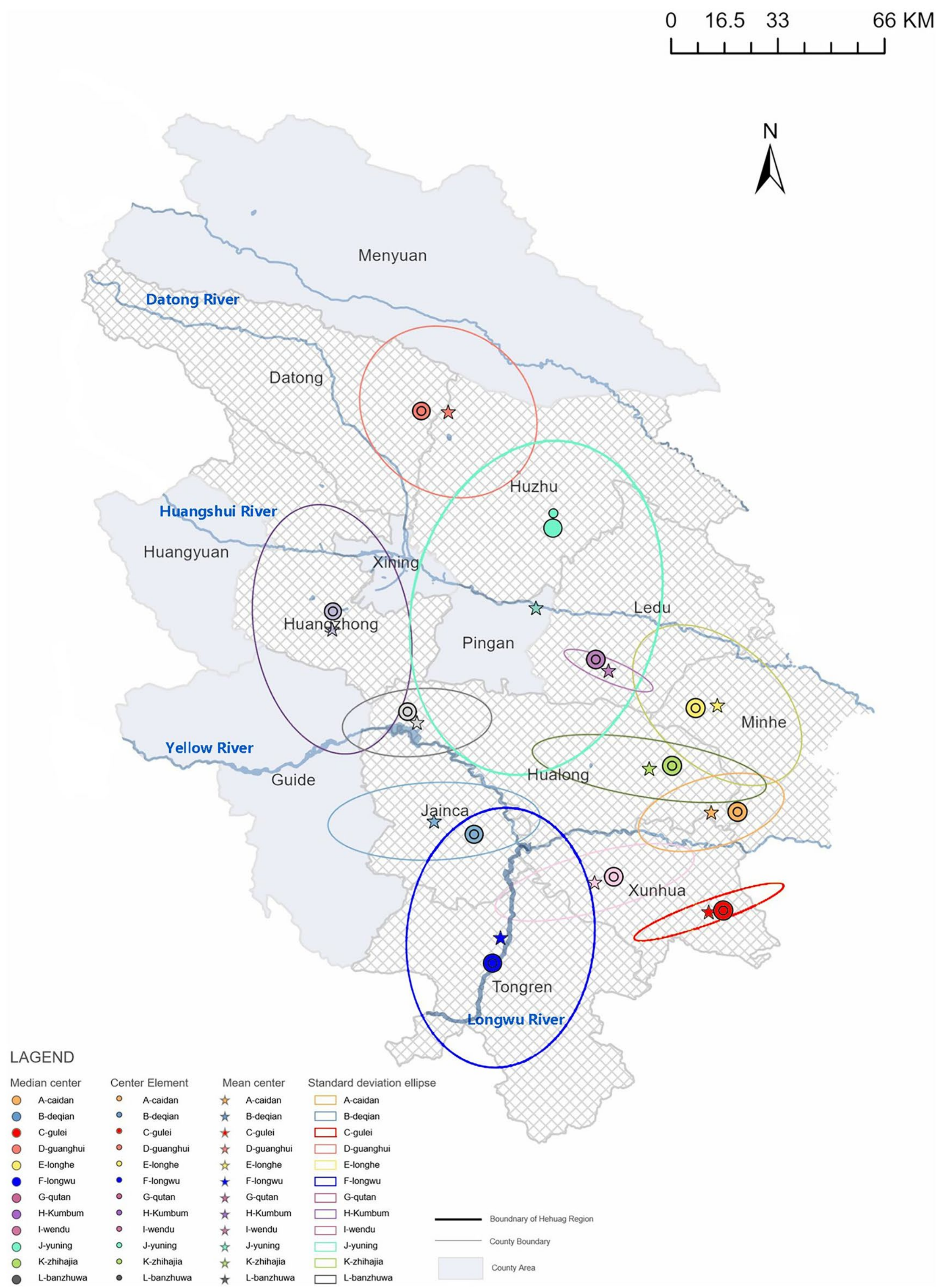


Fig. 10 Center and direction of principal-subordinate monastery system

Table 5 Mean Center and its neighboring principal monastery

System code	Mean center coord X	Mean Center Coord Y	NEAR principal Monastery	Distance between mean center and principal Monastery(km)	Near angle
A	826312.63	3982110.67	Principal A	6.6	3.78
B	756875.51	3977058.54	Principal B	10.7	−20.14
C	826835.44	3951381.71	Principal C	3.7	7.57
D	756656.08	4103499.93	Principal D	6.6	179.26
E	826613.69	4015234.33	Principal E	5.6	−169.32
F	774659.83	3941645.07	Principal F	8.2	−102.85
G	799060.74	4024964.23	Principal G	4.7	134.22
H	729745.26	4035585.02	Principal H	5.5	89.50
I	797793.29	3959473.79	Principal I	5.2	22.09
J	780317.08	4043701.72	Principal G	21.8	−44.82
K	810298.33	3995078.65	Principal K	5.7	10.82
L	751710.21	4007406.40	Principal L	4.1	125.62

monasteries. The Ming dynasty implemented the "multiple grants and construction" policy, granting titles and providing financial support to the Tibetan regions. For example, during the Hongwu period, the Qutan Monastery was built, and the Xining Buddhist Registry was established. These grants provided funding and elevated the status of the Buddhist elite, promoting the development of Tibetan Buddhist monasteries [20]. The Qing dynasty also implemented the "promote Gelug" policy, which supported monastery development through economic support and promotion. The Qing court granted titles such as Hutuktu and Zen master to the leaders of monasteries like Yuning Monastery, Kumbum Monastery, and Guanghui Monastery. In the fifty-first year of Qianlong (1786), Emperor Qianlong appointed the Jamyang Zhépa and Minzhur as important Buddhist leaders in the Hehuang region. These policies enhanced the social and political influence of the monasteries, promoting their concentration and development in the Hehuang region [77].

Geographically, the Hehuang region is a crucial area where multiple ethnicities converge, with the agriculture and animal husbandry intertwine. With relatively low altitudes, a mild climate, developed agriculture, economic growth, and convenient transportation, this region facilitates frequent cultural exchanges, fostering the establishment and flourishing of Tibetan Buddhism [48].

In addition, the kernel density distribution shows a gradual decrease from southeast to northwest, corresponding with the spatial distribution of principal monasteries. Specifically, the highest density of monasteries is found at the border of Hualong and Minhe, where the Zhihajia, Caidan, and Longhe monasteries are situated. In addition, prominent density of monasteries can be found in other areas such as the northern part of Tongren, central Huangzhong, northwestern Hualong, and eastern and western Xunhua. This is mainly due to the presence of principal monasteries like Longwu, Kumbum, Banzhuwa, Wendu, and Gulei. Although there are no principal monasteries in Guide, the adjacent regions contain principal monasteries such as Kumbum, Deqian, and Banzhuwa. Their subordinate monasteries extend into Guide, resulting in a high density of distribution in this area. Conversely, regions without principal monasteries, such as Datong, Menyuan, Huangyuan, Xining, and Ping'an, exhibit lower distribution densities. This distribution pattern not only reveals the intrinsic connection between the principal monasteries and kernel density distribution in the Hehuang region but also provides critical insights for understanding the region's religious and cultural distribution.

From the perspective of various sects, the geographical distribution characteristics of monasteries exhibit notable disparities. These differences are influenced not only by natural or social factors, but also potentially by the different doctrine and organizational structure of each sect [78]. The distinctive features of religious doctrines and organizational management among different sects may result in different spatial distribution patterns. Gelug monasteries in the Hehuang region exhibit a broad and dispersed spatial distribution. This is attributed to the Gelug sect's rigorous and systematic organizational structure, which forms a theocratic regime with a comprehensive and systematized approach to monastery construction, organizational systems, and educational methods. This organizational structure facilitates the extensive spatial distribution of Gelug monasteries, as they can better leverage political resources and organizational advantages to expand their influence and monastic network [24]. In contrast, the Nyingma sect's doctrines and organizational form are more primitive and loosely structured, with scattered monks and a lack of powerful monastic groups [79]. They maintain independence from local forces, resulting in Nyingma monasteries being more likely to concentrate within specific areas rather than widely dispersing.

Furthermore, the spatial distribution differences among monasteries of various sects may be closely related to the geographical location of their principal monasteries. In the Hehuang region, monasteries affiliated with Gelug dominate both in number and spatial density, aligning with the distribution of the ten principal Gelug monasteries in the area. In contrast, monasteries affiliated with Nyingma are more concentrated, primarily located in the eastern part of Hualong and along the border between Hualong and Guide. Correspondingly, there are only two principal monasteries of Nyingmapa: Zhihajia Monastery in eastern Hualong and Banzhuwa Monastery at the Hualong-Guide border, closely aligned with the dense distribution of Nyingmapa monasteries. This suggests a correlation between the dense areas of monasteries and the locations of their principal monasteries, further validating the notable influence of principal monasteries on the overall distribution of monasteries.

Spatial distribution characteristics of PSMS

Spatial pattern and formation reasons of PSMS

The aforementioned results highlight a spatial distribution pattern across all principal-subordinate monastery systems, characterized by the principal monastery being centrally located and surrounded by its subordinate monasteries. The underlying cause for the formation of this spatial relationship is its provision of numerous advantages and benefits for organizational management and doctrinal transmission within Tibetan Buddhism.

First, concerning organizational management and administrative efficiency, the principal monastery usually supervises subordinate monasteries by appointing key positions such as Khenpo and Khenzur to oversee religious activities and make major decisions [79]. This spatial arrangement, with the principal monastery at the core surrounded by subordinate monasteries, optimizes the coordination of religious activities, ceremonies, and administrative processes, ensuring orderly and efficient management. This also reinforces the principal monastery's leadership in both political and religious spheres [22].

Secondly, subordinate monasteries depend on financial and material support from the principal monastery for the maintenance, renovation, and expansion of their facilities. As the spatial center, the principal monastery can efficiently concentrate and distribute resources, providing comprehensive support in terms of finances, materials, personnel, and education, thus fostering the stability and development of the entire system [21].

Besides, in the realm of doctrinal transmission and religious propagation, the principal monastery serves as the cultural and educational hub, providing religious education and training for monks, thus supporting subordinate monasteries. This spatial relationship strengthens the doctrinal continuity among the monasteries. Additionally, the spatial distribution pattern of PSMS enhances the regional influence of the religion. Through the outreach efforts of the principal monastery, it promotes the dissemination and popularization of Tibetan Buddhist culture [23].

Spatial scale and formation factors of PSMS

Scale parameters and its relationships of PSMS Even though each PSMS exhibits a spatial clustering pattern with subordinate monasteries surrounding the principal monastery, their spatial scales such as the number of controlled subordinate monasteries, their distribution range, and hierarchical structure quite vary. To explore this result in depth, a scatter plot cluster diagram was generated using three parameters representing the spatial scale of each system (Fig. 11). The diagram uses color, the horizontal axis, and the vertical axis to represent spatial hierarchy, quantity scale, and range variability, respectively.

It illustrates that systems E, F, H, and J, which have multi-level hierarchical structures, demonstrate a larger number of subordinate monasteries and a broader range variability. In contrast, PSMS with a two-tier hierarchical structure show fewer subordinate monasteries and a smaller distribution range. This suggests that the hierarchical structure may positively influence the number and range of controlled subordinate monasteries. Furthermore, for PSMS with two-tier hierarchical structure, there is a general trend where an increase in the number of subordinate monasteries correlates with an expanded range variability aside from a few outliers. This supports the notion of a positive correlation between the number of subordinate monasteries and their range of control. Therefore, the scale of each PSMS is influenced by parameters such as hierarchical structure, the number of controlled monasteries, and their distribution range variability, with these factors showing a positive correlation among them.

Spatial scale influenced by different sectarian doctrine The varied spatial scales of different PSMS are influenced by factors deeply rooted in historical and cultural contexts. Firstly, diverse characteristics in religious doctrines and organizational management among different sects may account for the disparities in the hierarchical structures of PSMS. The Nyingma sect, as one of the

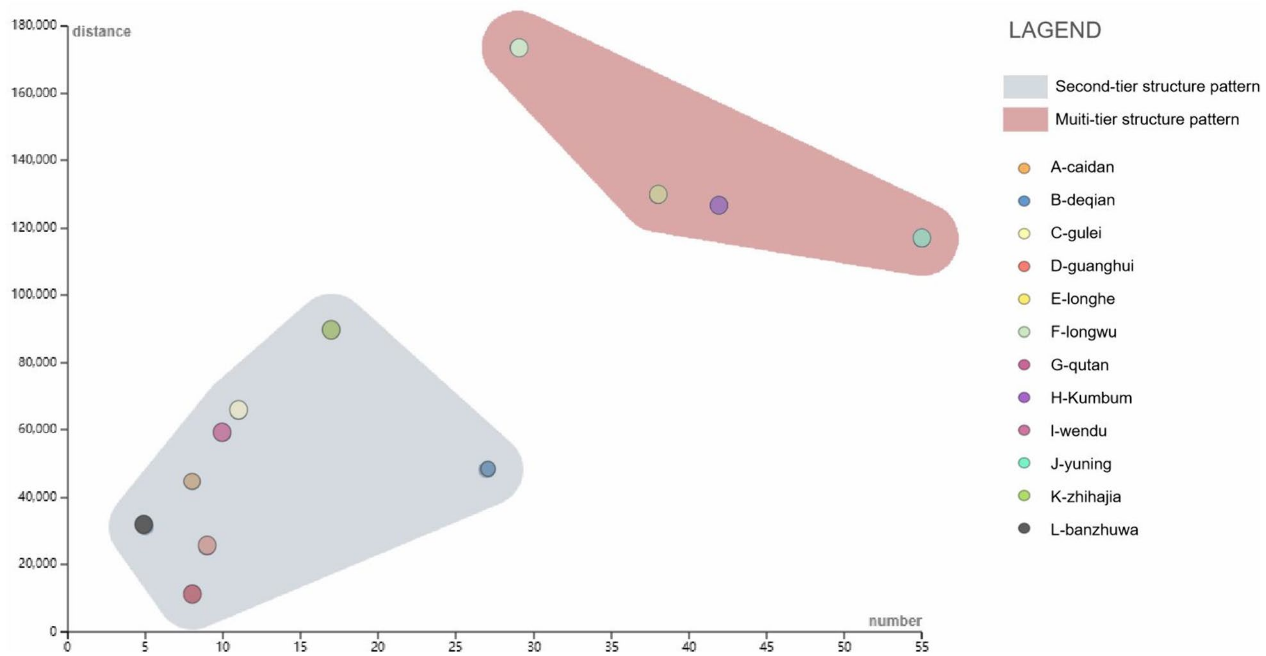


Fig. 11 The relationship between the hierarchy, amount, and range of PSMS

early sects of Tibetan Buddhism, demonstrates relatively primitive and loose doctrinal and organizational structures, with dispersed monks and monasteries. These monasteries maintain independence from local authorities, leading to a relatively consistent hierarchical structure with modest numbers and an uneven distribution range [67].For instance, within System L, there are only four subordinate monasteries, whereas within System K, the controlled range spans from within 20,000 m to over 900,000 km, illustrating apparent variations in control range. In contrast, the Gelug sect's close association with political power has led to a unified political-religious authority, resulting in a more organized and standardized system of monastery construction, organizational structures, and educational methods [23], reflected in a more uniform and sizable spatial distribution pattern.

Spatial scale influenced by different control modalities However, each PSMS of Gelug exhibits distinct spatial scales, likely influenced by the diverse management and control modalities. La categorized the PSMS in Qinghai Province into two control modalities, including one where both political and religious authority are vested in the principal monastery, and another where there is a only religious affiliation with the principal monastery but without political control [22].

In systems where both political and religious authority are centralized in the principal monastery, the principal monastery's acquisition of secular governance leads to smaller monasteries becoming completely subordinate both politically and religiously [29]. This dynamic creates a spatial distribution where subordinate monasteries cluster within a defined area. This form of hierarchical structure is predominant among the PSMS in Qinghai. For example, Principal G exercised both political and religious control over its seven subordinate areas, resulting in all subordinate monasteries being located within a 20,000 m radius [80]. Similarly, Principal D controlled its "five clans" within a 20–60 km range [21], indicating a deliberate limitation of its control area.

For the PSMS primarily linked by religious affiliation, there may not be strict distance limitations on the distribution of their subordinate monasteries. Although great geographical distances separate subordinate monasteries from the principal one, extending beyond its territorial boundaries, they maintain close ties in religious heritage and doctrinal matters, rather than direct political control [23]. For instance, within System J, there exists a wide-ranging distribution with considerable range variance. This is because the distant subordinate monasteries in System J are established or built by monks from the principal monastery in remote areas, primarily with strong religious affiliations rather than political governance ties [83]. Furthermore, in System F with a wide range variance, the senior monks of the principal monastery have established 18 meditation monasteries in different regions, which later became the subordinate monasteries [84]. This might illustrate that the PSMS within a certain range fall under a unified religious-political governance, while those beyond this range maintain a purely religious affiliation with the principal monastery.

Spatial scale influenced by different territorial sovereignty Furthermore, discrepancies in land control rights at the principal monastery contribute to variations in the scale of these amalgamated religious-political systems. Principal J, for instance, received patronage and support from leaders of various Mongolian tribes during its initial construction. This support endowed the monastery with extensive lands, population, and properties [81]. By the late 1940s, Principal J possessed over 50,000 mu (78.29 acres) of cultivated land [22]. Consequently, it established numerous subordinate monasteries within its territory. Similarly, the principal monastery H, with a large spatial scale, also controlled a considerable area, reaching over 100,000 mu (15.66 acres) by the 1950s [82]. In contrast, monasteries with smaller spatial scales, such as Principal D, controlled only nearly 10,000 mu (1.57 acres) of land, and Principal D possessed only 2,094 mu (3.29 acres) [21].

Spatial scale influenced by different religious magnitude In addition, the spatial scale may also be influenced by the religious magnitude of the principal monastery within those PSMS, such as the number of revered monks and reincarnated lamas, along with the frequency of their ennoblement. The reincarnation system of living Buddhas expands by enlarging principal monasteries or establishing more subordinate monasteries to enhance their authority and prestige [23]. For example, System J established diverse and complex reincarnation systems such as the Zhangjia, Tuguan, Songbu, and Quecang systems in its developmental trajectory, with a total of 54 subordinate monasteries [81]. Furthermore, the number of eminent monks receiving titles and honors may also correlate with the scale of the principal monasteries [22]. This can be seen from the scale of Systems J, K, and F, as they are bestowed with the most titles of Houtu Kektu, as well as the titles of Nomkhan and Banzhida [29].

In general, there is a notablevariation in the scale of PSMS, influenced by multiple parameters such as spatial hierarchy, quantity scale and range variability. A comprehensive analysis reveals that this variation stems from the diverse interplay of historical factors such as doctrinal characteristics of different sects, control modalities, territorial sovereignty, as well as religious magnitude of principal monasteries. Notably, the complexity of the system hierarchy, the abundance of subordinate monasteries, and the wide distribution range correspond to a richer historical and cultural background. For instance, System J, with the widest geographical spread and the highest hierarchical complexity, encompasses not only politically and religiously affiliated subordinate monasteries but also those with solely religious interactions. This system possesses extensive lands and boasts an importantreligious presence with numerous eminent monks and reincarnated lamas, reflecting the intricate historical and cultural factors underlying the differences in scale among PSMS.

Spatial scale influenced by natural and topographical factors The spatial direction of the PSMS shows a trend of correlation with the distribution of water system in Hehuang region. To provide evidence and further demonstrate the influence of natural elements on the PSMS, univariate chi-square tests were used to quantify the correlation between the natural influences of elevation and hydrology. This method of testing is commonly used to examine the correlation between the spatial distribution of samples and environmental factors, such as the study of ancient road restoration [78]. As shown in Table 6 and Table 7, the system A was chosen to be verified as an example for demonstration.

The univariate chi-square test uses the natural break classification method to categorize the elevation and hydrology data of Hehuang region into three levels. The second column lists the number of monasteries Q_i corresponding to the environmental factors within each level. The third column provides the area/distance for each level as determined by ArcGIS. The fourth column calculates the percentage for each level based on the classified area/distance. The fifth column computes the expected

Table 6 Univariate chi-square test of Elevation Factors for system A

Elevation	Number of monasteries Q_i	Classified area/ km^2	Percentage of classified area / %	The expected number of monasteries Ei under the null hypothesis H_O	Difference between observed and expected values χ^2
First Class(1796–1991)	2	608.58	3.07%	0.25	12.56
Second Class(1992–2712)	3	9533.10	48.02%	3.84	0.18
Third Class(2713–3216)	3	9710.50	48.91%	3.91	0.21
Sum of all	8	19852.19	100.00%	8.00	12.95

Table 7 Univariate chi-square test of Hydrological Factors for system A

Hydrological	Number of monasteries Q_i	Classified area/ km^2	Percentage of classified area / %	The expected number of monasteries *Ei* under the null hypothesis H_O	Difference between observed and expected values χ^2
First Class(0–364.06)	4	4760.66	16.50%	1.32	5.44
Second Class(364.06–1224.08)	1	9931.40	34.41%	2.75	1.12
Third Class(1224.08–2893.83)	3	14168.27	49.09%	3.93	0.22
Sum of all	8	28860.33	100.00%	8.00	6.78

number of monasteries in each level based on the data in the second and fourth columns. Based on this, a hypothesis test is performed as follows:

a. Formulate the null hypothesis H_O: The distribution of monasteries is independent of the different environmental factors.
b. Under H_O, calculate the test statistic χ^2 using the following formula:

$$\chi^2 = \Sigma \frac{(f_0 - f_e)^2}{f_e}$$

c. The calculated χ^2 value, since the four environmental factors are divided into three levels, follows a chi-square distribution with 3–1 = 2 degrees of freedom. Referring to the standard chi-square distribution table, at a 0.05 significance level, the chi-square value for 2 degrees of freedom is 5.99.

As shown in Table 8, seven monastery clusters have an χ^2 value less than 5.99 for the elevation factor, indicating no significant correlation. In contrast, only three monastery clusters show no significant correlation with the hydrology factor. Overall, for the 12 PSMSs, the correlation with elevation is only 41%, whereas the correlation with hydrology reaches 75%. This demonstrates that the distribution of most PSMS monasteries is closely related to rivers, while their association with mountains is comparatively weaker.

This correlation arises because the Hehuang region, a major agricultural area in Qinghai with a high population density, has historically been a frontier for the spread of Tibetan Buddhist culture to eastern Tibet. The relatively narrow valley leads to a densely clustered and perpendicular distribution along the riverbanks. In contrast, the Yellow River basin, being more extensive and broader, leads to a distribution pattern where systems are spread along its banks because the river acts as a natural barrier. Furthermore, the Datong and Longwu Rivers, which are significant northern and southern tributaries of the Yellow River in the Hehuang region, support Tibetan communities that predominantly reside along these rivers. Consequently, the principal-subordinate monastery systems are oriented almost perpendicular to these rivers. This analysis reveals that most PSMS in the Hehuang region are influenced by the river systems. They display distribution patterns that either align with or run perpendicular to the river courses based on the characteristics of the respective waterways.

Conservation application to other heritage

The PSMS, with its principal monastery at its core and subordinate monasteries distributed in clusters around it, offers a novel approach to the conservation of cultural heritage. Its analytical framework can be employed as a reference point and applied to the conservation of other heritage clusters.

Reference to the hierarchical structure of the PSMS

The hierarchical structure of the Tibetan Buddhist PSMS exhibits a common feature with other religious heritages, which provides a scientific basis for the prioritisation of conservation work and the allocation of resources. The Tibetan Buddhist PSMS is notable for its hierarchical structure, which can also be found in other religious heritages. These include the diocesan network of the Catholic Church, the system of autonomous churches of the Eastern Orthodox Church, the close-knit network of Buddhist Zen monasteries, the system of the main mosque and the neighbouring community mosques of Islam, and the network of the main temple and the local temples of Hinduism. Despite the differences in cultural roots, geographical background and organizational forms, these systems might exhibit certain patterns and characteristics in their spatial layout. Furthermore, the determination of their spatial hierarchical structure and main center enables the PSMS to identify the monasteries with significant influence. Similarly, other types of heritage clusters can also identify key and influential heritages

Table 8 Results of univariate chi-square test for environmental factors for 12 PSMS

System	Principal monastery	Difference between observed and expected values for elevation χ^2	Difference between observed and expected values for distance to water χ^2
A	Caidan Monastery	12.95	6.78
B	Deqian Monastery	2.54	23.72
C	Gulei Monastery	1.96	3.52
D	Guanghui Monastery	1.52	6.40
E	Longhe Monastery	72.75	25.54
F	Longwu Monastery	4.60	25.48
G	Qutan Monastery	2.11	2.96
H	Kumbum monastery	17.71	17.87
I	Wendu Monastery	2.81	2.86
J	Yuning Monastery	6.80	14.23
K	ZhiHajia Monastery	0.13	6.09
L	Banzhuwa Monastery	18.36	7.22

on the basis of their internal hierarchical structure, which can provide a basis for prioritization and resource allocation for conservation.

Reference to the systematic pattern of the PSMS

The culture-based, systematic categorisation of Tibetan Buddhism can provide a basis for spatial planning of heritage conservation under an approach to cultural heritage that prioritises integrity. Tibetan Buddhism categorizes monasteries into different PSMS based on differences in the living Buddha system and the lineage of the teachings. Although other cultural or religious heritage may not adhere to the same logic of classification, they may exhibit diverse typologies based on the context of the spread of their own culture and history. Such typologies extend beyond the scope of individual conservation or group conservation within administrative districts, being based on cultural ties intrinsic to the area in question. This approach allows for a more complete and coherent conservation, effectively avoiding the cultural fragmentation that may otherwise result from a misguided approach to conservation. Furthermore, analogous to PSMS, the dense spatial distribution of heritage groups is frequently the area with the most prominent religious or cultural ambience, which serves as a crucial reference point for the delineation of cultural zones. Moreover, the direction and accessibility of the heritage cluster provide a basis for the investigation of the trajectory of religious and cultural transmission. Consequently, the analytical framework of PSMS, which encompasses the distribution patterns of density, main center, range, and direction, provides a novel and integrated perspective that can be employed in other culture heritage clusters.

Reference to the social-natural contexts of the PSMS

The close links between PSMS with society and nature provide a broader conservation mechanism for other types of heritage conservation. PSMS is not only deeply rooted in the natural environment, but are also closely linked to all aspects of social life. This characteristic is also reflected in other types of heritage, where the layout of PSMS is often influenced by natural factors such as the distribution of watercourses. Furthermore, the vast majority of cultural heritage is faced with similar influence factor in terms of the natural environment. It is therefore important to consider the potential impact of the natural environment on heritage sites and to implement measures aimed at the protection of the ecosystems and natural landscapes in the immediate vicinity of such sites. In addition, other heritage forms, including PSMS, are closely connected to neighbouring communities or villages, forming intricate and vibrant cultural tapestries through religious ceremonies, festivals, and other communal activities. Consequently, in the process of heritage conservation, it is essential to reinforce a profound comprehension of the cultural practices prevailing within the local communities. This can be achieved by establishing an efficacious mechanism for the participation of these communities, thereby encouraging them to collaborate in the protection and advancement of cultural heritage.

Practical significance of conservation monasteries as PSMS

Integrated perspective of heritage conservation

In contrast to prior conservation efforts that focused on individual monasteries, a more comprehensive approach has been taken with the division of monasteries into distinct heritage clusters based on the PSMS for integrated conservation. This methodology provides a comprehensive and holistic perspective on the conservation of heritage, offering an novel strategy for the conservation of monastic heritage.

This is due to the fact that a conservation approach which considers monasteries as a cluster ensures that the integrity of the cultural heritage is maintained and reflected. The World Heritage Convention places a significant emphasis on the concept of integrity as a fundamental assessment criterion for the nomination of World Heritage sites. Tibetan Buddhist monasteries represent a comprehensive system of governance and religion, founded upon the historical and cultural divisions of the teachings, the living Buddha system, and the ruling administration. Previously, the conservation of monastic heritage was typically confined to individual monasteries, with an emphasis on the evaluation and protection of their architectural features, cultural artifacts and historical significance. One limitation of this approach was an insufficient appreciation of the interconnectedness of monastic heritage within a larger context of history and culture. However, PSMS provides a framework for investigating the historical connection and cultural correlation between the principal monasteries and their subordinate monasteries. Furthermore, this historical and cultural link has been further substantiated by physical evidence of the spatial distribution pattern of the PSMS. This has led to the formulation of a novel approach to heritage conservation, based on the delineation of each principal monastery system.

Furthermore, this approach offers a cultural regional reference point for the safeguarding of monastery heritage, diverging from the prevailing strategy of conservation based on administrative divisions. This novel approach to heritage conservation, which is predicated on the subdivision of each PSMS, serves as a foundational reference point for the preservation of disparate categories of cultural areas. This approach diverges from traditional conservation strategies based on administrative areas, which have been identified as potentially leading to the neglect or fragmentation of cultural ties. In contrast, this strategy provides a systematic and comprehensive approach to conserving monastic heritage.

Prioritized allocation of conservation resources

A model centred on the principal monastery in PSMS has the potential to facilitate the establishment of priorities for heritage conservation and achieve a more efficient allocation of resources. Previously, the approach to the conservation of monasteries was unclear and lacked a defined focus. The implementation of traditional conservation strategies may result in an imbalanced distribution of resources, particularly in regions where resources are scarce or management levels are disparate. However, this study establishes the cultural and geographic centrality of the principal monastery, as well as the linkages and hierarchies between the principal and subordinate monasteries. The prioritisation of conservation efforts can be conducted in accordance with the status and influence of the monastery in question within the system. By prioritising the protection of the principal monastery, the conservation of the subordinate monasteries can be driven, thereby ensuring a more targeted and efficient use of resources. This approach will not only maintain the overall stability of the system, but also help to ensure the continued cultural value and influence of the system as a whole, avoiding the lack of protection that would otherwise result from the dispersal of resources.

Rational tourism route of cultural conservation

The spatial distribution characteristics of the principal monasteries provide a reference basis for the development of reasonable tourism routes. This study employs a classification system based on the primary monastery system to categorise Tibetan Buddhist monasteries. This reveals that monasteries within this system are typically situated in particular geographical regions, thereby establishing a foundation for the delineation of diverse Tibetan Buddhist cultural areas. In general, monasteries situated within the same cultural area are linked by historical and cultural ties. This indicates the possibility of establishing a range of tourist destinations with shared cultural characteristics, based on the different PSMS. Moreover, the creation of itineraries based on the accessibility of the PSMS could foster a more profound public comprehension of the cultural heritage associated with these institutions. This, in turn, has the potential to contribute to the preservation and revitalisation of this cultural heritage.

Community participation of collaborative conservation

Adopting a conservation strategy founded on a PSMS framework can facilitate the formation of a collective sense of heritage identity. Adopting a conservation strategy founded on a PSMS framework can facilitate the formation of a collective sense of heritage identity. In accordance with their sectarian lineage and living Buddha system, the Tibetan populace holds veneration for a variety of monasteries. The religious, cultural, administrative and spatial connections between principal and subordinate monasteries result in the inextricable linking of the communities in which they are located. Consequently, adherents within the same Tibetan Buddhist cultural area may exhibit a heightened degree of identity and involvement, whereas those in disparate Tibetan Buddhist cultural areas may espouse disparate beliefs, despite being situated within the same administrative region. Conventional conservation techniques may fail to take into account the specific cultural and religious context of the community, leading to a lack of community identification and engagement in conservation initiatives. A comprehensive approach to the conservation of the PSMS can more effectively reflect and support the religious and cultural practices of the local community, fostering a stronger sense of identity and participation in the heritage. Active community involvement is crucial for the implementation of conservation measures and the long-term sustainability of cultural heritage.

Conclusions

The PSMS in Tibetan Buddhism is a unique cultural phenomenon that holds importantvalue in both historical and spatial research. However, current research predominantly focuses on the spatial distribution of monasteries based on different sects or specific Tibetan regions, and mainly focuses on its history and religions, while overlooking the external manifestation patterns revealed through spatial distribution characteristics. Concurrently, the analytical framework of the PSMS guarantees the intrinsic cultural connections and integrity of cultural heritage, as well as the prioritisation of conservation and the allocation of resources in accordance with scale and impact, with the objective of preserving clusters of heritage through the planning of tourist routes and the promotion of community participation. This study, using Hehuang region as a case study, developed a novel research framework to analyze the spatial distribution of PSMS,so as to comprehensively examine the overall and system-specific spatial distribution characteristics of Tibetan Buddhist monasteries and analyze the contributing factors behind their spatial patterns. Thus, the study offers an analysis framework for diverse and multi-tiered heritage clusters that are interconnected by religious and cultural ties, providing a foundation for further research and exploration. The following findings were obtained:

(1) From an overall perspective, Tibetan Buddhist monasteries in the Hehuang region exhibit a pronounced spatial clustering pattern, with uneven characteristic across different areas and sects. In addition to historical and geographical factors, the study demonstrates a notable correlation between the overall density of monastery distribution and the location of principal monasteries.

(2) From the perspective of individual PSMS, each system exhibits a spatial distribution pattern with the principal monastery as the geographical center and its subordinate monasteries clustered around it. Within these systems, over 88% of subordinate monasteries are located within 60,000 m of their principal monastery. As the distance increases, the number of subordinate monasteries gradually decreases. Additionally, the clustering of these systems often correlates geographically with the county in which the principal monastery is located. This distribution pattern enhances organizational management and efficiency, optimizes resource allocation and support, and promotes the transmission of teachings and the spread of religion.

(3) While each PSMS tends to form clusters, the scale of these systems varies under the control of their principal monasteries. This variation involves parameters such as spatial hierarchy, quantity scale and range variability, which exhibit a roughly positive correlation. The differences in scale are primarily attributed to multiple historical factors, including doctrinal characteristics of different sects, control modalities, territorial sovereignty, as well as the religious magnitude of principal monasteries. The orientation of the PSMS is closely related to the distribution of rivers, but its relationship with mountain ranges is minimal and requires further exploration.

Limitations

The research scope in the Hehuang region is relatively narrow as it does not include the consideration of monasteries located in other areas within the PSMS. This omission may lead to some degree of error in the research results. Therefore, future studies need to broaden the scope of research to gather more comprehensive data.

The primary focus of this paper is to analyze the spatial distribution characteristics of principal-subordinate monastery systems, without delving into the temporal and spatial backgrounds or site selection factors of monastery establishment. It is hoped that future research will conduct in-depth analysis in these areas.

Furthermore, due to space constraints, this paper only focuses on the influence of principal monasteries on monastery distribution, with brief mentions of other natural, historical, and geographical factors. Future research can further enrich the content in these areas.

Acknowledgements

Thanks to the Professor Tongtong Liu's studio and Plateau Provincial Key Laboratory of Energy and Environment for providing data.

Author contributions

Conceptualization: Tongtong Liu, Weijia Li Data curation: Weijia Li, Yue Zhang Formal analysis: Weijia Li, Huanjie Liu, Yuan Li, Shuangying Li Funding acquisition: Weijia Li, Yuan Li, Shuangying Li Investigation: Weijia Li, Huanjie Liu Methodology: Weijia Li, Huanjie Liu Project administration: Tongtong Liu, Weijia Li, Yuan Li, Shuangying Li Resources: Weijia Li Software: Weijia Li, Huanjie Liu Supervision: Tongtong Liu Validation: Tongtong Liu, Weijia Li, Yue Zhang Visualization: Weijia Li Writing –original draft: Weijia Li Writing –review & editing: Weijia Li, Tongtong Liu, Huanjie Liu.

Funding
This work was supported by the National Natural Science Foundation of China (Grant numbers 52366019), and Tianjin University Postgraduate Arts and Sciences Topnotch Innovation Award Program 2022 (Grant numbers A1-2022–005).

Availability of data and materials
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
The research has received ethical approval from the Tianjin University and Qinghai Minzu University. It is noteworthy that the study has not included any human or animal studies.

Competing interests
The authors declare no competing interests.

Received: 24 May 2024 Accepted: 3 September 2024
Published online: 27 September 2024

References

1. Chapagain NK. Heritage conservation in the Buddhist context. Asian Heritage Management: Routledge; 2013.
2. Teleki K. Heritage, development, and concerns of Mongolia's monasteries. Trans-Himalayan Buddhism: Routledge; 2019.
3. Li Z, Hou M, Dong Y, Wang J, Ji Y, Huo P. Research on the digital retention mechanism of Tibetan Buddhism architecture based on Uav and Tls: a case study of Baoguang hall. ISPRS annals of the photogrammetry, remote sensing and spatial information sciences Copernicus GmbH, 2021; VIII-M-1–2021: 95–100.
4. Campbell A. What the emperor built: architecture and empire in the early Ming. Washington: University of Washington Press; 2020.
5. Zhang J, Ren Y. The historical and architectural origins of palace buildings in the Kumbum Monastery from a multicultural perspective. J Asian Archit Buil Eng Taylor Francis. 2023;22(4):2074–93.
6. Tuo Y, Zhou B, Shang D. Combination of the Chinese and Tibetan architectural languages——a case study of three halls of wusutuzhao in inner Mongolia. IOP Conf Series Mater Sci Eng IOP Publish. 2019;592(1): 012120.
7. Yang X, Ji X, Cao Y, Yu T. Studies on wall painting materials and techniques at two historic buildings in Gyantse. Tibet Herit Sci. 2019;7(1):40.
8. Martin N. The Wanla group of monuments: 14th-century Tibetan Buddhist murals in Ladakh. Euro Bull Himalayan Res. 2022. https://doi.org/10.4000/ebhr.788.
9. Tythacott L, Bellini C. Deity and display: meanings, transformations, and exhibitions of Tibetan Buddhist objects. Relig Multidisc Dig Publish Inst. 2020;11(3):106.
10. Keyworth GA. Chinese and Tibetan sources on the Dhāraṇī in roll seven of the *Śūraṃgama-sūtra. Stud Chinese Relig. 2022;8(1):99–142.
11. Erendzhenova YY. Russian centers of the Tibetan buddhist tradition: Features and significance of religious practices. New Res Tuva. 2021;13:156–68.
12. Bear L, Avieli N, Feldman J. UNESCO World heritage sites: shared shrines or contested sanctuaries? the case of the Buddhist monasteries of Luang Prabang Laos. J Herit Tourism. 2021;16(1):1–19.
13. Zu X, Gao C, Wang Y. Towards religious landscape: protection of Tibetan Buddhist heritage in Aba Prefecture. Int J Appl Earth Obs Geoinf. 2024;130: 103885.
14. Xu X, Zhang J, Liu S, Liu J, Zhang Z, Tian X. Entropy change of historical and cultural heritage in traditional tibetan area of china based on spatial-temporal distribution pattern. Build Multidisc Dig Publish Inst. 2023;13(12):2995.
15. Wu J, Fang Y. Study on the protection of the lama monastery heritage in inner Mongolia as a cultural landscape. J Asian Archit Build Eng Taylor Francis. 2016;15(1):9–16.
16. Dukpa Z. The history and development of monastic education in bhutan. In: Schuelka MJ, Maxwell TW, editors. Education in Bhutan: Culture, Schooling, and Gross National Happiness. Singapore: Springer; 2016. p. 39–55.
17. Lempert M. Interaction rescaled: how monastic debate became a diasporic pedagogy. Anthropol Educ Quart. 2012;43(2):138–56.
18. Zhang Y, Zhang H, Sun Z. Effects of urban growth on architectural heritage: the case of Buddhist monasteries in the Qinghai-tibet plateau. Sustain Multidisc Dig Publish Inst. 2018;10(5):1593.
19. Cui N, Wu T, Wang Y-C, et al. Buddhist monasteries facilitated landscape conservation on the Qinghai-Tibetan Plateau. Landscape Ecol. 2022;37(6):1559–72.
20. Pu W. Tibetan Buddhist monasteries in Qinghai. Gansu: Gansu Nationalities Publishing House; 2013.
21. Zhu P. A geographical study of the history and culture of Tibetan Buddhism in Qinghai province. Shaanxi: Shaanxi Normal University; 2006.
22. La J. Historical and cultural study of the Gelugpa principal monastery system. Chaoyang: China Tibetology Press; 2016.
23. La J. On the system of Tibetan Buddhism's principal subordinate monasteries and the reasons for its formation-taking Qinghai Gelugpa monastery as an example. Chinese Tibetol. 2015;4:82–91.
24. Lama D, Berzin A. Part I. an introduction to mahamudraand its practical application to life. The Gelug/Kagyu tradition of mahamudra. USA ed. edition. Ithaca, N.Y: Snow Lion, 1997: 19–33
25. Kollmar-Paulenz K. History writing and the making of Mongolian Buddhism. Archiv für Religionsgeschichte De Gruyter. 2018;20(1):146.
26. Kozicz G. The onpo lhakhang of sumur. notes on the neglected nyingmapa tradition of nubra. Études mongoles et sibériennes, centrasiatiques et tibétaines CEMS/EPHE. 2020;51:1–26.
27. Shi J, Jin Y. A linguistic study of Tibetan village and monastery symbiosis patterns in Huangshui based on "space and event." Archit J. 2021;1:40–6.
28. Ba K. History of Sumba Buddhism (in Tibetan). Lanzhou: Gansu Nationalities Press; 1992.
29. Guan B. History of politics and religion in Amdo (in Tibetan). Gansu: Gansu Nationalities Press; 1982.
30. Si S. History of the gelugpa teachings - the yellow glazed treasure (Tibetan). Beijing: China Tibetology Press; 1989.
31. Chen W. An examination of seerke monastery's subordinate monasteries. Qinghai Soc Sci. 2011;6:119–25.
32. Pu W. Zhazang monastery and Cheshin Nomun Khan. China Tibetol. 2013;1:86–91.
33. Zhang J. Historical study of Ta'er monastery's architecture in Qinghai. Xi'an Univ Archit Technol 2020.
34. Jie Y. A Study on the historical cultural geography of Buddhism in northwest China. Shaanxi Normal University, 2004.
35. Ming Shilu. Shanghai bookstore publishing house, 2015.
36. Tongren country annals compilation committee. Tongren Country Annals. Sanqin: Sanqin Publishing House; 2001.
37. Yang Y. New annals of Xining prefecture. Qinghai: Qinghai People's Publishing House; 1954.
38. Chao Z, Zhao Y, Liu G. Multi-scale spatial patterns of Gelug monasteries of Tibetan Buddhism in Tibetan Inhabited Regions. China GeoJournal. 2022;87(5):4289–310.
39. Chao Z, Zhao Y, Fang S, Chen D. Spatial diffusion processes of Gelug monasteries of Tibetan Buddhism in Tibetan areas of China utilizing the multilevel diffusion model. Geo-Spat Inform Sci Taylor Francis. 2022;0:1–18.
40. Wang K. An Experimental study on the spatial distribution of Tibetan Buddhist Sakya monasteries in kham and their characteristics in the historical period. Study Relig. 2011;3:178–83.
41. Fang S, Zhao Y, Chao Z, Kang X. Spatial distribution characteristics and influencing factors of Tibetan Buddhist monasteries in Amdo Tibetan inhabited regions, China. J Geovisualiz Spat Anal. 2022;6(2):1–25.
42. Fang S, Zhao Y, Liu X, Yang Y. Quantitative characteristics and influencing factors of Tibetan Buddhist religious space with monasteries as the carrier: a case study of U-Tsang, China. Herit Sci. 2024;12(1):93.
43. Han Y, Li H, Zhu X, Yang C. A study on the spatial and temporal distribution characteristics of Tibetan Buddhist monasteries in Qing Alxa Banner. World Archit. 2021;4:82–6.
44. Peng W, Yang Y, Huang Y, Zou K, Duan K, Shen Y. Spatial differentiation characteristics and influencing factors of Buddhist monasteries in Yunnan Province. Trop Geography. 2024;44(2):315–25.

45. Zhu L, Su H, Zhang P, Li Z. Spatial and temporal evolution of Tibetan Buddhist monasteries in Qinghai Province. World Reg Stud. 2019;28(2):209–16.
46. Xiao Y, Guo L, Zhou S, Li F, Wu B. GIS-based distribution and land use pattern of the monasteries in guoluo Tibetan autonomous prefecture in China. In: Bian F, Xie Y, editors. Geo-Informatics in Resource Management and Sustainable Ecosystem. Berlin, Heidelberg: Springer; 2016. p. 190–6.
47. Chen D, Zhao Y, Chao Z, Li Y, Fang S. Constructing a digital system of historical geographic information from the perspective of digital humanities: a case study of the historical geographic information database of Tibetan Buddhist monasteries. Dig Scholar Human. 2024;39(1):43–60.
48. Xu B, Mao X, Li X, et al. Anthropogenic activities dominated the spatial and temporal changes of normalized difference vegetation index (NDVI) in the Hehuang valley in the northeastern Qinghai Province between 2000 and 2020. Front Environ Sci Front. 2024. https://doi.org/10.3389/fenvs.2024.1384032.
49. Comprehensive expedition to the loess plateau, chinese academy of sciences. The natural environment and its evolution in the loess plateau region. Science Press, 1991.
50. Li Z, Hou M, Dong Y, Wang J, Ji Y, Huo P. Research On the digital retention mechanism of Tibetan Buddhism architecture based On Uav And Tls: a case study of Baoguang hall. 2021, 95–100.
51. Yan-Jun L, Jing-Fan H. Investigation and type analysis of traditional residential buildings in Qinghai section of "Silk Road." E3S Web Conf EDP Sci. 2021. https://doi.org/10.1051/e3sconf/202128302004.
52. Sifei L. Tubo-Sogdian relations along the silk road: on an enigmatic gold plaque from Dulan (Qinghai, China). Iran Caucasus Brill. 2022;26(4):309–22.
53. Pu W. Historical changes of Tibetan Buddhism in Huangshui Region. Qinghai Soc Sci. 2000;6:95–100.
54. Powers J. Tsongkhapa. The Buddhist World: Routledge; 2015.
55. Wende Z, Hou G, Chen H, Jin S, Zhuoma L. Dynamic changes in forest cover and human activities during the Holocene on the northeast Tibetan plateau. Front Earth Sci Front. 2023. https://doi.org/10.3389/feart.2023.1128824.
56. Ma X, Zhang H. Land-use/land-cover change and ecosystem service provision in Qinghai province, china: from the perspective of five ecological function zones. Land Multidisc Dig Publish Inst. 2023;12(3):656.
57. Zhu P. Mountains and Tibetan Buddhist Monastic Architecture. Qinghai Ethnic Stud. 1997;4:36–9.
58. Qi G. A study of Tibetan Buddhist policies Andthe formation of Gelug monastic groups in the Qing dynasty. Northwest Normal University, 2021.
59. Zhu J, Xu W, Xiao Y, Shi J, Hu X, Yan B. Temporal and spatial patterns of traditional village distribution evolution in Xiangxi, China: identifying multidimensional influential factors and conservation significance. Herit Sci. 2023;11(1):261.
60. Li C, Qian Y, Li Z, Tong T. Identifying factors influencing the spatial distribution of minority cultural heritage in Southwest China. Herit Sci. 2024;12(1):117.
61. Liu Y, Liu L, Xu R, Yi X, Qiu H. Spatial distribution of toponyms and formation mechanism in traditional villages in Western Hunan, China. Herit Sci. 2024;12(1):171.
62. Li X. Determination of the temporal–spatial distribution patterns of ancient heritage sites in China and their influencing factors via GIS. Herit Sci. 2024;12(1):143.
63. Mitchell A. The Esri guide to Gis analysis, modeling suitability, movement, and interaction. Esri: Esri Press; 2012.
64. Zhou J, Jiang Y, Liu J, Tan L, Meng L. Evaluation of Chinese traditional military settlements' defensive capabilities via principal component analysis (PCA): a case study of coastal Wei forts in the Ming dynasty. Herit Sci. 2024;12(1):100.
65. Yang J, Xiang Q, Chen Y, Zhu D, Zhang C. Multiple attribute constraint and nearest-neighbour provincial summary method for farmland quality database. Nongye Jixie Xuebao/Transactions Chinese Soc Agricu Machinery. 2014;45(10):300–6.
66. Huang Q, Liu X, Wu J, et al. Application of spatial analysis methods and apriori association rule algorithm in the analysis of spatial distribution characteristics of traditional villages in Anhui province. 2023 IEEE International Conference on Sensors, Electronics and Computer Engineering (ICSECE). 2023: 332–340.
67. Alevkayali Ç, Dindar H. Spatial and temporal distribution of earthquakes in Cyprus and its surroundings: a geostatistical approach. Yerbilimleri/Earth Sci. 2022;43(3):197–211.
68. Ma X, Zhang Y, Li Y, Li Y, Lin F. Spatial–temporal distribution and evolution of the socialist built heritage in China, 1949–1978. Herit Sci. 2023;11(1):214.
69. Mehta V, Bawa S, Singh J. Analytical review of clustering techniques and proximity measures. Artif Intell Rev. 2020;53(8):5995–6023.
70. Burt E, Barber M, Rigby L. Elementary statistics for geographers. 3rd ed. Guilford: The Guilford Press; 2009.
71. Canham CD, Uriarte M. Analysis of neighborhood dynamics of forest ecosystems using likelihood methods and modeling. Ecol Appl. 2006;16(1):62–73.
72. Getis A, Franklin J. Second-order neighborhood analysis of mapped point patterns. In: Anselin L, Rey SJ, editors. Perspectives on Spatial Data Analysis. Berlin, Heidelberg: Springer; 2010. p. 93–100.
73. Chen S, Wang X, Qiang Y, Lin Q. Spatial–temporal evolution and land use transition of rural settlements in mountainous counties. Environ Sci Eur. 2024;36(1):38.
74. Durlević U, Novković I, Carević I, et al. Sanitary landfill site selection using GIS-based on a fuzzy multi-criteria evaluation technique: a case study of the City of Kraljevo. Serbia Environ Sci Pollut Res. 2023;30(13):37961–80.
75. Chen T. Quantitative archaeology. Beijing: Peking University Press; 2005.
76. Tan L, Liu H, Zhou J, et al. A GIS-based modeling approach for determining the efficiency of the traffic system between ancient military castles. Discret Dyn Nat Soc. 2021;2021(1):6329935.
77. Zhang J, Ren Y, An X. Temporal and spatial features of the palace building space of Qinghai's Kumbum Monastery and its evolution. PLOS ONE Public Lib Sci. 2022;17(10): e0262155.
78. Wang L, Zhou Z. A Study on the sectarian geographic differentiation in the distribution of Tibetan Buddhist monasteries in the contiguous Region of Yunnan, Tibet and Sichuan. Geograph Res Dev. 2017;36(3):171–6.
79. La J. The history and local characteristics of the formation of Tibetan Buddhist sects in the perspective of Chineseization. Chinese Tibetol. 2022;1:50–60.
80. Wang Q, Wu C. Gautama temple. China Construction Industry Press, 2018.
81. Liu M, Ou Y. Domainization of Tibetan Buddhist Gelugpa Monasteries in the Ming and Qing Periods-the case of Yuning monastery. Trop Landform. 2022;43(1):65–70.
82. Qinghai provincial local records compilation committee. Qinghai Province: religion. Xi'an Publishing House, 2000.
83. Guan B. History of politics and religion in Amdo. Gansu: Gansu Nationalities Publishing House; 1982.
84. Ji M. Longwusi temple record. Qinghai: Qinghai Nationalities Press; 1988.

Publisher's Note