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Spatial patterns of Geological Culture Villages (Towns) and their influential factors in China

Yunxing Zhang^{1*}, Zhenyu Zhang¹, Chenchen Lu¹, Meiyu Yang¹, Zhengyu Zhao¹ and Cuihua Gu^{2*}

Abstract

Geological Culture Villages Towns (GCV(T)s) serve as rich repositories of geological resources, embodying significant historical and cultural values that mirror the dynamic interplay between Earth's evolution and human societies. Despite their importance, the theoretical underpinnings of GCV(T)s have not been thoroughly explored and elucidated. This study explores the relationship between geological culture and societal development, revealing the linkage between geological culture and societal advancement with the aim of promoting a harmonious coexistence between humanity and the environment. Focusing on 96 GCV(T)s in China, this study employs spatial analytical techniques such as the nearest-neighbor index, kernel density analysis, geographic connectivity, and geographic detector to scrutinize the spatial distribution patterns and identify key influencing factors. The findings reveal that (1) GCV(T)s exhibit uneven distribution, with concentrations in the Yangtze River Delta region, Beijing-Tianjin-Hebei region, and Shanxi-Gansu and Ningxia Provinces. (2) These sites tend to be situated in areas characterized by active geological formations, abundant geological relics, higher elevations, gentle topography, and ample rainfall. (3) The establishment and evolution of GCV(T)s are shaped by a complex interplay of geological heritage, natural factors, and human interventions. While the selection and spatial arrangement of these sites are predominantly influenced by geological and natural factors, the innovative development of their geological cultural heritage is driven by humanistic considerations. Overall, the distribution and evolution of GCV(T)s stem from multifaceted interactions among diverse factors. Recognizing this intricate web of influences is crucial for safeguarding geocultural diversity and formulating conservation strategies for geoheritage protection. The development of GCV(T)s transcends mere geoheritage preservation, it embodies a pivotal stride toward safeguarding the varied and multi-dimensional global geoheritage.

Keywords Geological Culture Villages (Towns), Spatial distribution, Influencing factor, Geocultural, Geoheritage

Introduction

Geoheritage represents geological phenomena resulting from the Earth's internal and external geological forces or their combined processes [1, 2]. The exploration and conservation of geological heritage have evolved from spontaneous and conscious efforts to systematic research [3–5]. Although global appreciation and awareness of geological heritage have increased, as demonstrated by the rise in thematic publications and practical initiatives at the global and national levels in the past decade, the recognition of the value of geological heritage remains

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inadequate in many areas [6]. Nevertheless, with growing awareness of the importance of preserving geological heritage, numerous countries and regions have prioritized its protection [7, 8]. Economically developed countries, such as the United States [9], Canada [10], and the United Kingdom [11] are at the forefront of managing geological heritage protection, having established stringent laws, regulations, and effective conservation measures [12–17]. This protection aims to achieve two goals: the preservation of these invaluable heritage sites and the promotion of their sustainable utilization in tourism. [18–21]. Until the early twentieth century, geology focused more on the aesthetic aspects rather than the specific geological value of abiotic elements in nature for the conservation of geological heritage [22, 23]. This approach operated on the premise that certain geological heritage is a part of natural heritage and should be managed to ensure protection and sustainable use. The current trajectory emphasizes the establishment of geoparks and the advancement of geotourism centered on geoheritage [22, 24–31]. As of 2023, the World Geoparks Network encompasses 195 geoparks from 41 countries and territories [32, 33]. While global efforts have increased, this study turns its focus to China, where boast abundant and diverse geological heritage resources and a total of 2,265 geological heritage sites [34]. From 2001 to 2023, 272 national geoparks have been established [19, 35–39]. Notably, a large proportion of geological heritage sites do not fulfill the criteria for designations similar to geoparks, thereby encountering challenges in conservation and utilization. Geological sites primarily underscore earth sciences and natural history, forming a striking contrast with cultural sites that emphasize historical and cultural progression. Despite this distinction, a pivotal intersection exists between these realms, particularly manifest in tourism and educational contexts [40, 41]. This convergence propels the progress of both geological and cultural tourism, fortifying the connections between rural tourism and traditional villages. It satiates the longing for natural wonders and scientific understanding, while also providing profound insights into local histories and cultural traditions. However, a paucity remains in the hubs that intertwine geo-cultural heritage, rural tourism, and traditional villages.

The Ministry of Natural Resources of China has introduced the concept of Geological Culture Villages (Towns), abbreviation GCV(T)s, as a response to the social phenomenon. This novel research area combines the disciplines of geology, heritage, sociology, and tourism to create a new type of village and town that integrates geo-heritage resources, cultural resources, characteristic agricultural resources, and tourism resources [42–44].

GCV(T)s represent a fresh approach to geological heritage protection, succeeding scenic spots, tourist attractions, geoparks, and geosite protection zones, meanwhile, it also serves as a new model for development after beautiful villages, characteristic towns, traditional villages, among others [45, 46]. The preservation and safeguarding of GCV(T)s are critical for the conservation of geological heritage, the transmission of history and culture, the development of an ecologically sustainable civilization, and the promotion of rural tourism.

Currently, numerous interdisciplinary studies focus on the conservation of geological heritage, encompassing fields such as geology, geography, anthropology, and tourism. These studies are categorized into three primary perspectives [47]. First, from the standpoint of geological heritage conservation, research is directed towards the classification, construction characteristics, conservation awareness, and organization and management of GCV(T)s [48–51]. Second, from a cultural heritage perspective, studies examine the cultural essence of GCV(T)s, rural culture revitalization, and the cultural tourism value [52–55]. Third, from a sustainable development viewpoint, research delves into rural tourism development, geotourism, and ecological protection [35, 56, 57]. Nevertheless, there is limited focus on the protection of geological heritage, cultural value dissemination, and rural tourism development, particularly concerning GCV(T)s. Furthermore, past studies have mainly focused on quantitative and empirical research on the factors of spatial distribution of regional traditional villages [58–61], and some of the studies have focused on theoretical analysis and case applications [62, 63], there is a paucity of quantitative and empirical studies on the factors influencing the regional and spatial distribution of GCV(T)s.

Thus, this study aims to employ the three batches of 96 traditional villages published by the Chinese Geological Society since 2021 [64–66]. Utilizing GIS technology and mathematical and statistical methods, the spatial distribution of GCV(T)s in China is characterized, and the relationships between GCV(T)s distribution and geological and natural factors are examined. Additionally, Geo Detector technology is employed to explore the relationship between human factors and the spatial distribution pattern of GCV(T)s, considering both single and interactive factors. This aims to enable the government to comprehend the spatial distribution characteristics and patterns of GCV(T)s in China, optimize the protection of geological heritage and tourism development, devise targeted and efficient protection and construction measures, and furnish scientific foundations and references for safeguarding and cultivating the world's geological heritage resources.

This study provides a scientific basis and reference for the conservation and development of the world's geological heritage resources.

Materials and methods

Data sources

In this study, data were collected through two primary methods. Firstly, information pertaining to three batches of 96 distinctive GCV(T)s (26 in the initial set, 24 in the second set, and 46 in the third set) were retrieved from the official website of the Chinese Geological Society (<http://first.geosociety.org.cn/dzwhc/>). These GCV(T)s were assigned Baidu coordinates and a GCV(T) database was established using ArcGIS 10.8 to facilitate spatial analysis. The second dataset comprises the GCV(T)s spatial distribution influencing factors dataset, encompassing geological, natural, and human resource data. Geological resource data, such as the quantity of geological relics, geologic hazards, and fault information, came mainly from the Center for Resource and Environmental Science and Data (<https://www.resdc.cn/>) at the Institute of Geographic Sciences and Resources, Chinese Academy of Sciences. Natural resource data, including elevation, geomorphology, river system, climate, precipitation, and vegetation information, were obtained from the National Earth System Science Data Center (<https://www.geodata.cn/>). Human resource data were predominantly derived from the China Statistical Yearbook, while socioeconomic, tourism, and cultural resource data were extracted from the China Statistical Yearbook 2022, regional statistical yearbooks, and relevant statistical bulletins published by the National Bureau of Statistics (<https://www.stats.gov.cn/>). Additional data were acquired from official websites of the National Bureau of Statistics, the Ministry of Land and Resources, and other relevant sources. Table 1 would be provided in the list of abbreviations.

Methods

This research employs spatial statistical analysis techniques to investigate the spatial distribution pattern, kernel density, regional differentiation

characteristics, and spatial autocorrelation analysis of characteristic GCV(T)s (Fig. 1). Key methods utilized include kernel density analysis, closest proximity index, disequilibrium index, spatial autocorrelation analysis, local correlation index, and geographical contact rate. Detailed calculation formulas are provided in the formulas. Kernel density estimation is applied to examine the distribution patterns and traits of point features across different spatial domains. Based on previous studies, Jenks's natural discontinuity classification method was applied to establish consistent parameters for analysis using ArcGIS 10.8 software. By employing ArcGIS 10.8 surface analysis slope tools, we utilized natural breaks methods to reclassify China's DEM data, which were subsequently superimposed onto GCV(T)s. A kernel density analysis tool was employed to generate a kernel density map illustrating the spatial aggregation patterns of GCV(T)s across the nation. The primary purpose of the closest proximity index is to evaluate the mutual nearness amongst characteristic GCV(T)s and to identify the type of spatial distribution. The Lorentz curve concentration index calculation method is utilized for the disequilibrium index to evaluate the distribution equilibrium of characteristic GCV(T)s within various provinces and regions. The geographic contact rate is used to analyze the association between the spatial distribution of characteristics and the regional economy, as well as the distribution characteristics of national relics and national geological parks [67].

Formulas

Nearest Neighbor Index

The Nearest Neighbor Index (NNI) is a geographic index that indicates the degree of proximity of point-like objects in geographic space, providing insights into the spatial distribution characteristics of point-like elements [68]. In this study, the NNI was utilized to identify the spatial distribution of the three batches of GCV(T)s in China. The calculation formula is as follows:

$$\begin{cases} r_E = \frac{1}{2\sqrt{n/A}} = \frac{1}{2\sqrt{D}} \\ R = \frac{r_1}{r_E} = 2\sqrt{D}r_1 \end{cases} \quad (1)$$

where n is the number of points, A is the area of the region, D is the density of points, R is the nearest neighbor index, r_1 is the average distance between the closest points, and r_E is the theoretical nearest neighbor distance. When $R < 1$, the GCV(T)s tend to be clustered; when $R > 1$, the GCV(T)s are uniformly distributed; and when $R = 1$, the GCV(T)s are randomly distributed.

Table 1 The list of abbreviations

Full name	Abbreviations
Geological Culture Villages Towns	GCV(T)s
Nearest Neighbor Index	NNI
Geographic Concentration Index	G
Geographic detector	GD
Gross Domestic Product	GDP

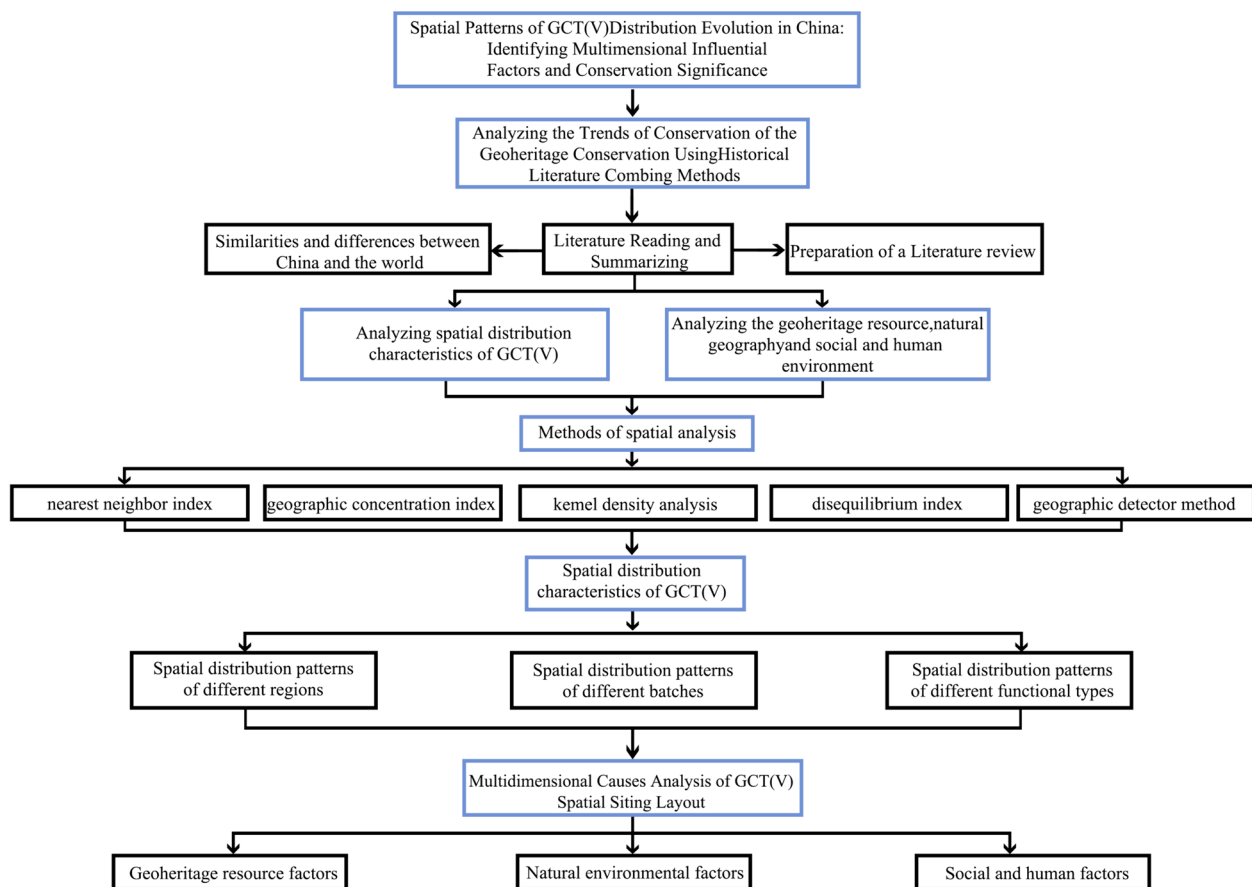


Fig. 1 Research flow chart

Geographic Concentration Index

The Geographic Concentration Index (G) is primarily used to measure the degree of concentration of the spatial distribution of samples in geographical space [58]. It evaluates the agglomeration of characteristic GCV(T)s in the actual spatial distribution. A larger G value indicates that the characteristic GCV(T)s are concentrated in a specific region; conversely, a smaller G value suggests a more dispersed distribution. The calculation formula of G is as follows:

$$G = 100 \times \sqrt{\sum_{i=1}^n \left(\frac{x_i}{T}\right)^2} \tag{2}$$

In this equation, G represents the geographic concentration index, X_i represents the number of characteristic GCV(T)s in the i th province, T indicates the total number of characteristic GCV(T)s, and n indicates the total number of provinces.

Disequilibrium Index

The Disequilibrium Index (S) is an index reflecting the distribution of point-like elements and can be used to analyze the balanced distribution of characteristic GCV(T)s in various provinces and regions in China. In this study, the Lorenz curve was introduced to further reflect the imbalance of GCV(T)s. The Lorenz curve represents the cumulative proportion of variables and ranks them from low to high [69]. The calculation formula is as follows:

$$S = \frac{\sum_{i=1}^n \gamma_i - 50(n + 1)}{100n - 50(n + 1)} \tag{3}$$

In this equation, S indicates the disequilibrium index, n indicates the number of provinces and regions, and Y_i indicates the number of GCV(T)s in each province and is sorted from largest to smallest.

Kernel density estimation

Kernel density estimation is a statistical technique that reflects the characteristics of spatial dispersion or concentration by testing the regional spatial variation in sample point density [70], thereby determining the dispersion of the concentration and area samples. The calculation formula is as follows:

$$F(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x - X_i}{h}\right) \tag{4}$$

In this equation, $F(x)$ indicates the estimated value of the kernel density of GCV(T)s, n indicates the number of GCV(T)s, $x - X_i$ indicates the distance from the estimated point x to sample X_i , $h > 0$ indicates the bandwidth, and K indicates the spatial weight function.

Geographic connection rate

The geographical connection rate (V) was used to analyze the impact of tourism resource endowments on the spatial distribution of GCV(T)s in geological relics in China. Geoheritage was selected as the measurement index of geological resource endowment. The geographic connection rate ranged from 0 to 100 [59]. The greater the value is, the greater the degree of spatial coincidence between GCV(T)s and geological resource endowments, and the closer the spatial connection between them. The calculation formula is as follows:

$$V = 100 - \frac{1}{2 \sum_{i=1}^n |x_i - y_i|} \tag{5}$$

where V indicates the geographical connection rate, x_i indicates the proportion of GCV(T)s in the i th province to the total number of GCV(T)s in China, and y_i indicates the proportion of the number of geoheritage sites in the i th province to the total number of geoheritage sites in China.

Geographic detector

The geographic detector (GD) method is a statistical method used to explore the spatial variations in geographical elements and reveal the underlying driving forces. Spatial differentiation phenomena and their driving factors are detected by analyzing the relationship between the variance within a specific attribute layer and the total variance. The core advantage lies in its ability to investigate the interaction effects of two overlaying factors [60]. Considering the complexity of the factors influencing the spatial distribution of GCV(T)s, this study opted for a combination of single-factor and multifactor

interaction detection methods for comprehensive investigation. The expression is as follows:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2} \tag{6}$$

where $h = 1, 2, \dots$; L is the strata of the GCV(T)s, N is the number of samples, N_h is the sample number of type h , δ_h^2 is the variance of the affected index of Y of type h , and δ_i^2 is the variance of the affected factor. Typically, the value of q lies between 0 and 1. The closer the q value is to 1, the greater the impact of the factor on the affected index.

Results

Spatial distribution characteristics

In 1935, Hu Huanyong proposed the population demarcation line, known as the Tengchong-Heihe Line or Hu Huanyong Line [71]. It bisects China into approximately two equal parts, extending from Heihe to Tengchong. Figure 1 illustrates significant variations in the distribution of GCV(T)s in different regions, such as xiangxi province [58], henan province [59], guizhou province [60], fujian province [61]. Specifically, 96 GCV(T)s (85.42%) are situated to the east of the Heihe-Tengchong Line, while 14 GCV(T)s (14.58%) lie to the west. Analysis of the regions on either side of the Hu Huanyong Line (Fig. 2) reveals an east–west spatial distribution pattern characterized by high density in the east and lower density in the west, indicative of clear meridional regional differentiation tendencies. At the provincial level, the 96 GCV(T)s across China are distributed among 27 provinces, autonomous regions, and municipalities under the direct administration of the central government (excluding Hong Kong, Macao, and Taiwan). Owing to disparities in natural conditions, human factors and economic factors, and levels of development among provinces, substantial variations exist in the distribution of GCV(T)s. Zhejiang Province has the highest number of GCV(T)s at 13, followed by Anhui, Shandong, Hubei, Fujian, Hunan, Gansu, Jilin, Yunnan, and Hebei. Provinces with more than 4 GCV(T)s collectively account for over half of the total number of regions.

In this study, the average nearest distance tool was used to determine that the actual nearest distance r_1 is approximately 134,119.4954 m, whereas the theoretical nearest distance r_E for the spatial distribution of GCV(T)s in the provincial administrative regions of China is around 169,731.2737 m. The R value calculated using the formula (1) $R = 0.79$ was found to be less than one, indicating a clustered spatial distribution pattern of GCV(T)s.

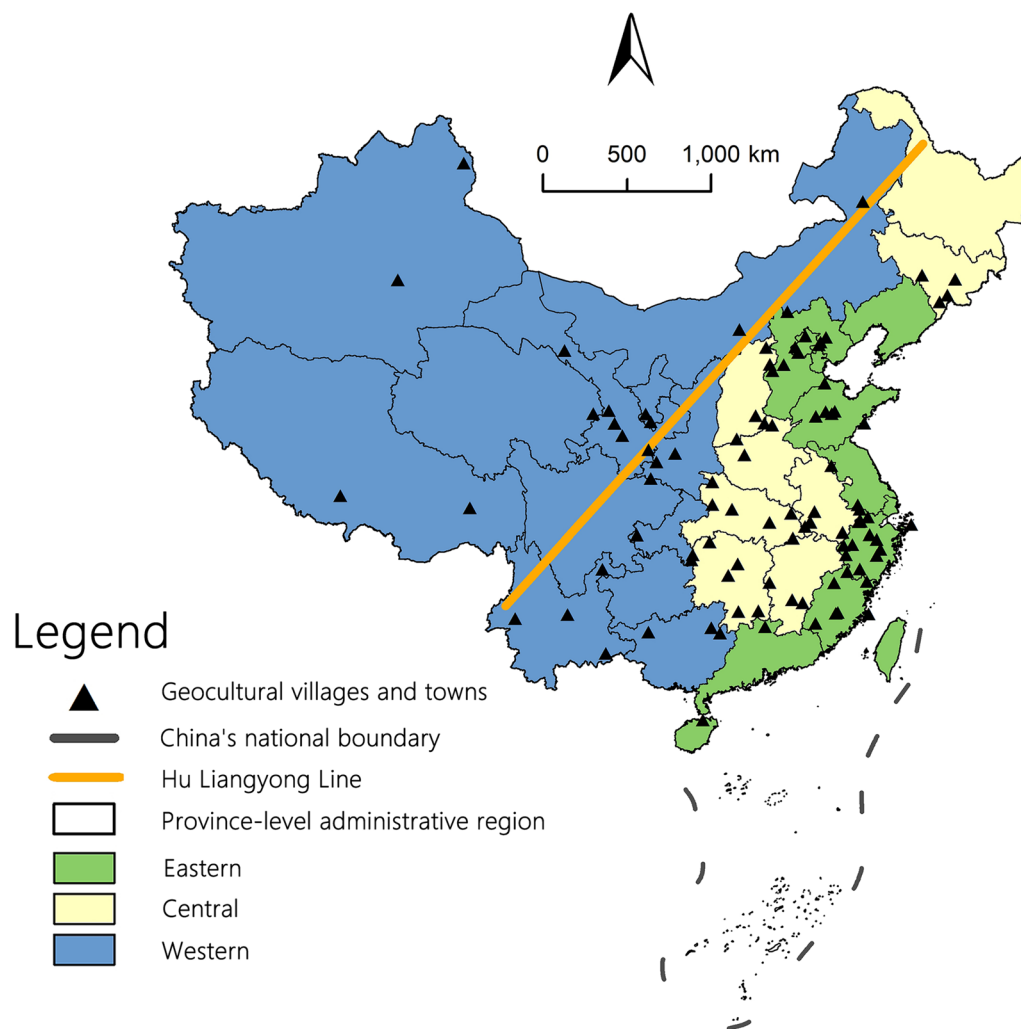


Fig. 2 Spatial distribution of GCV(T)s in China

The geographic concentration index (G), a metric assessing the degree of geographic concentration, was employed to examine the concentration of GCV(T)s across China's provincial administrative regions. The geographic concentration index for GCV(T)s in these regions was computed as $G=23.34$. G_1 was introduced as the geographic concentration index for GCV(T)s in individual provincial administrative regions, calculated as $G_e=19.25$. The comparison between G and G_1 revealed an increase in GCV(T)s concentration. Combined with the nearest neighbor index and geographic concentration index, the spatial distribution pattern of GCV(T)s was determined to be clustered. Figure 2 illustrates the spatial layout of GCV(T)s in China, highlighting a concentration in the eastern and central regions contrasted with a scattered distribution in the west.

The imbalance index of GCV(T)s, calculated as 0.35 using Eq. (4), confirmed the uneven national distribution

of GCV(T)s. In Fig. 3, the Lorenz curve depicted a distinctly convex shape, indicating an imbalanced distribution of GCV(T)s in China [72]. The analysis of the number, percentage, and cumulative percentage of GCV(T)s across provinces and regions revealed a consistent pattern (Table 2).

Spatial distribution density

As depicted in Fig. 4, the map reveals the presence of one high-density agglomeration center, two medium-density agglomeration centers, and several dispersed low-density areas. Specifically, a high-density agglomeration center is situated in the Yangtze River Delta region, encompassing parts of Jiangsu, Zhejiang, and Anhui provinces. The two medium-density agglomeration centers are identified in the Beijing-Tianjin-Hebei region, comprising Beijing and Tianjin municipalities, and in the provinces of Shanxi, Gansu, and Ningxia. Furthermore, diverse low-density

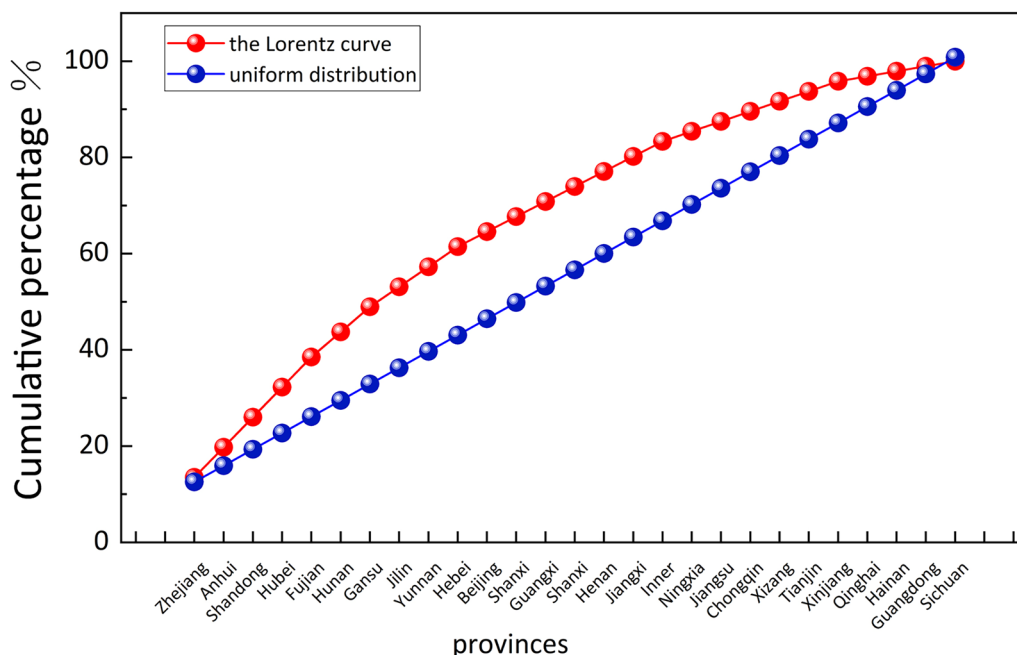


Fig. 3 The Lorenz curve of the distribution of GCV(T)s in China

clusters of GCV(T)s distributed across several other provincial administrative regions, including Jilin, Henan, Hubei, and Hunan provinces.

Establishment of different types of GCV(T)s

The China Geological Society has categorized the construction mode of GCV(T)s into six categories: geology + eco-tourism, geology + eco-agriculture, geology + nature education, geology + ecological recreation, geology + innovation and creativity, and six additional categories. Table 3 illustrates the varied and extensive construction modes currently adopted for GCV(T)s in China, though there exists an imbalance in the distribution of these modes. The predominant construction approach observed is the geology + eco-tourism model, implemented in 43 sites, whereas the geology + innovation and creativity model is the least utilized, present in only 4 sites. Alongside nature education, comprehensive service-oriented construction is relatively prevalent, whereas eco-recreational and eco-agricultural construction modes demonstrate lower frequencies. This highlights that GCV(T)s development predominantly emphasizes cultural and tourism aspects, with opportunities for enhancing other construction modalities. Disparities in geo-cultural and regional economic development levels contribute to divergent construction strategies for GCV(T)s projects across regions, necessitating tailored approaches based on local resource conditions and developmental potentials.

Factors influencing the spatial distribution of GCV(T)s

Geological resources

Geoheritage denotes the invaluable and irreplaceable geological phenomena that have been shaped, evolved, and preserved through diverse internal and external geological processes over the extensive history of Earth’s geological evolution. Categorized based on factors such as discipline, origin, management, protection, scientific value, and aesthetic value, geological relics are classified into 3 categories, 13 categories, and 46 subcategories [73, 74].

GCV(T)s center around the geoheritage landscapes, imbued with distinct scientific significance, and exhibit a pronounced spatial correlation with geological conditions. Consequently, throughout Earth’s prolonged geological timeline and influenced by both intrinsic and extrinsic geological forces, China’s geological relics and structures have undergone further development and transformation, forming a spectrum of geological relics that significantly influence the distribution of GCV(T)s [75]. As shown in Fig. 5, the geological relics originating from geological activities serve as valuable assets for the establishment of national GCV(T)s, with their spatial occurrence notably overlapping with that of GCV(T)s. Predominantly situated at the convergence points of geological tectonic units, GCV(T)s are particularly concentrated at the junctures of the North China Block and the Yangtze Block [76], due to the vigorous

Table 2 Statistics on the number of GCV(T)s in China's provinces and regions

Area	First batch	Second batch	Third batch	Total number	Proportion (%)	Cumulative proportion (%)
Zhejiang	4	4	5	13	13.54	13.54
Anhui	2	1	3	6	6.25	19.79
Shandong	2	3	1	6	6.25	26.04
Hubei	2	2	2	6	6.25	32.29
Fujian	3	1	2	6	6.25	38.54
Hunan	1	1	3	5	5.21	43.75
Gansu	1	0	4	5	5.21	48.96
Jilin	0	1	3	4	4.17	53.13
Yunnan	0	1	3	4	4.17	57.29
Hebei	3	0	1	4	4.17	61.46
Beijing	0	0	3	3	3.13	64.58
Shanxi	1	1	1	3	3.13	67.71
Guangxi	1	0	2	3	3.13	70.83
Shanxi	0	0	3	3	3.13	73.96
Henan	1	1	1	3	3.13	77.08
Jiangxi	3	0	0	3	3.13	80.21
Inner Mongolia	0	1	2	3	3.13	83.33
Ningxia	0	0	2	2	2.08	85.42
Jiangsu	0	1	1	2	2.08	87.50
Chongqing	0	1	1	2	2.08	89.58
Xizang	0	2	0	2	2.08	91.67
Tianjin	0	1	1	2	2.08	93.75
Xinjiang	1	0	1	2	2.08	95.83
Qinghai	0	1	0	1	1.04	96.88
Hainan	1	0	0	1	1.04	97.92
Guangdong	1	0	0	1	1.04	98.96
Sichuan	0	1	0	1	1.04	100.00
Total	27	24	45	96	100.00	100.00

geological tectonic movements in these regions, leading to an abundance of geoheritage resources and a substantial number of GCV(T)s demonstrating a cohesive spatial pattern.

The endowment of geoheritage resources constitutes a pivotal factor influencing the advancement of GCV(T)s in a region [77]. Within the existing evaluation and management criteria for geological and cultural villages in China, the geological resource endowment level is predominantly assessed through geological relics [78]. These relics serve as prime exemplars of premium, well-endowed, and high-value geological resources, indicative of the developmental prospects of regional geological tourism. The Ministry of Natural Resources has announced 2265 world-class and national geoheritage sites in China, which serve as benchmark indicators of regional geological tourism resource endowment. The study examined the relationship between geological resource endowment and the spatial

distribution of GCV(T)s, demonstrating a geographical correlation rate of 99.43% and underscoring their tight interrelation.

Natural resources

Altitude constitutes a key attribute of GCV(T)s and a vital index for quantitative research (Fig. 6) [79]. The map layout demonstrated that, in general, GCV(T)s were situated in low- and medium-elevation regions. By tallying the number of GCV(T)s at different altitudes (Fig. 7), we discovered that 54 GCV(T)s were distributed across altitude intervals less than 521 m, accounting for approximately 56% of all GCV(T)s; moreover, 74% of GCV(T)s were located in areas below 1181 m in altitude. The results revealed that the higher the altitude was, the lower the number of GCV(T)s, indicating a negative correlation between GCV(T)s distribution and altitude.

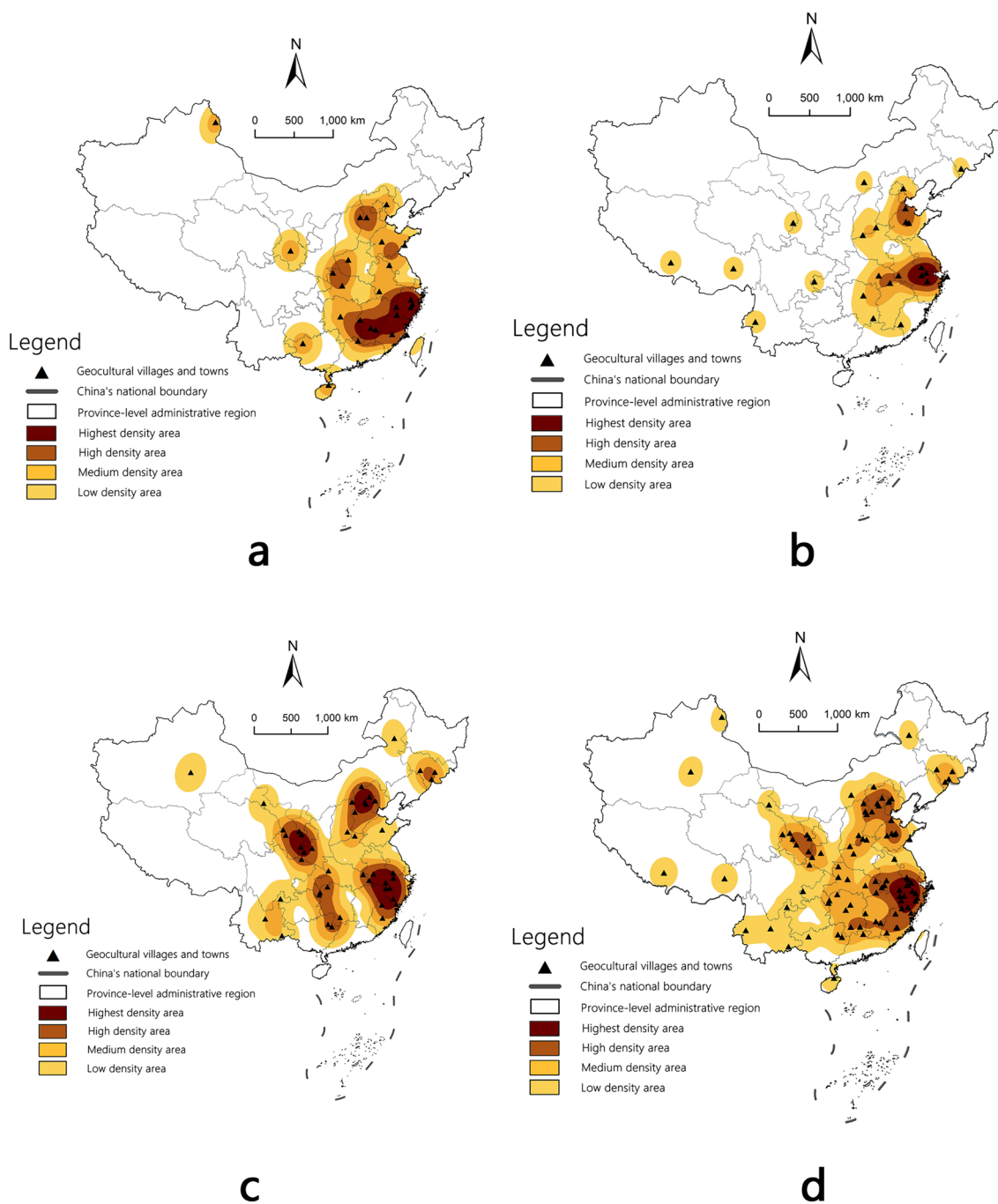


Fig. 4 The kernel density analysis of the distribution of GCV(T)s in China. **a** The first batch of GCV(T)s in China. **b** The second batch of GCV(T)s in China. **c** The third batch of GCV(T)s in China. **d** All batches of GCV(T)s in China

River

River systems are essential for the development of GCV(T)s, providing fundamental material guarantees for human production and life [80]. As shown in Fig. 8, through overlay analysis, GCV(T)s were primarily concentrated in the middle and lower reaches of the

Yangtze River, the upper and lower reaches of the Yellow River, and the middle and lower reaches of the Pearl River. River systems not only provide water resources for production and life in villages and towns but also regulate transportation modes and climate [81, 82], while suitable hydrological conditions facilitate the development and

Table 3 Statistics on the number and categories of GCV(T)s

Mode	Acronym	Five-star	Three-star	Listing preparation	Total
Geology + Innovation	G+I	0	2	2	4
Geology + Ecological Wellness	G+EW	0	1	9	10
Geology + Eco-tourism	G+ET	0	16	27	43
Geology + Ecological Agriculture	G+EA	0	3	4	7
Geology + Nature Education	G+NE	1	7	10	18
Geology + Integrated Services	G+IS	0	4	10	14
Total	T	1	33	52	96

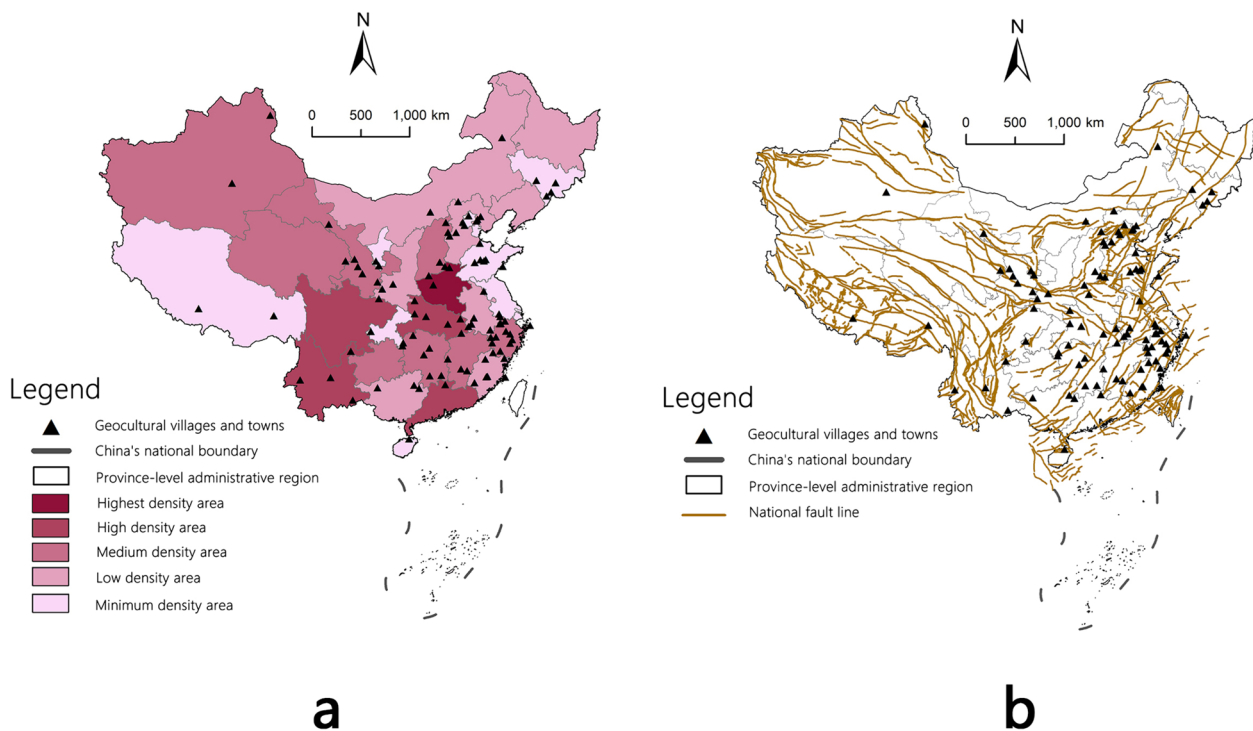


Fig. 5 a Spatial distribution of geological relics b GCV(T)s and fault distribution

construction of GCV(T)s by creating beautiful natural landscapes.

Climate

Climate disparity often determines the difference in precipitation in a region, temperature and precipitation are important factors in shaping landscapes of agricultural production and tourism landscapes in GCV(T)s [83]. When combined with China’s climate divisions, the Beijing-Tianjin region and the Jiangsu-Zhejiang region situated on the eastern coast are exposed to a unique monsoon climate, characterized by warm and humid monsoon currents from the Pacific Ocean, abundant precipitation, and simultaneous rain and

heat. These favorable climatic conditions have laid a strong natural foundation for agricultural production and promoted the formation of distinctive agricultural landscapes. Consequently, the GCV(T) clusters are located in the subtropical and warm temperate regions of South China, East China, Central China, and North China (Fig. 8). The monsoon climate, precipitation, and temperature promote conducive conditions for large-scale developments in production and life in geological villages and towns.

Vegetation

Vegetation can preserve its ecological appearance and community characteristics in GCV(T)s, constituting

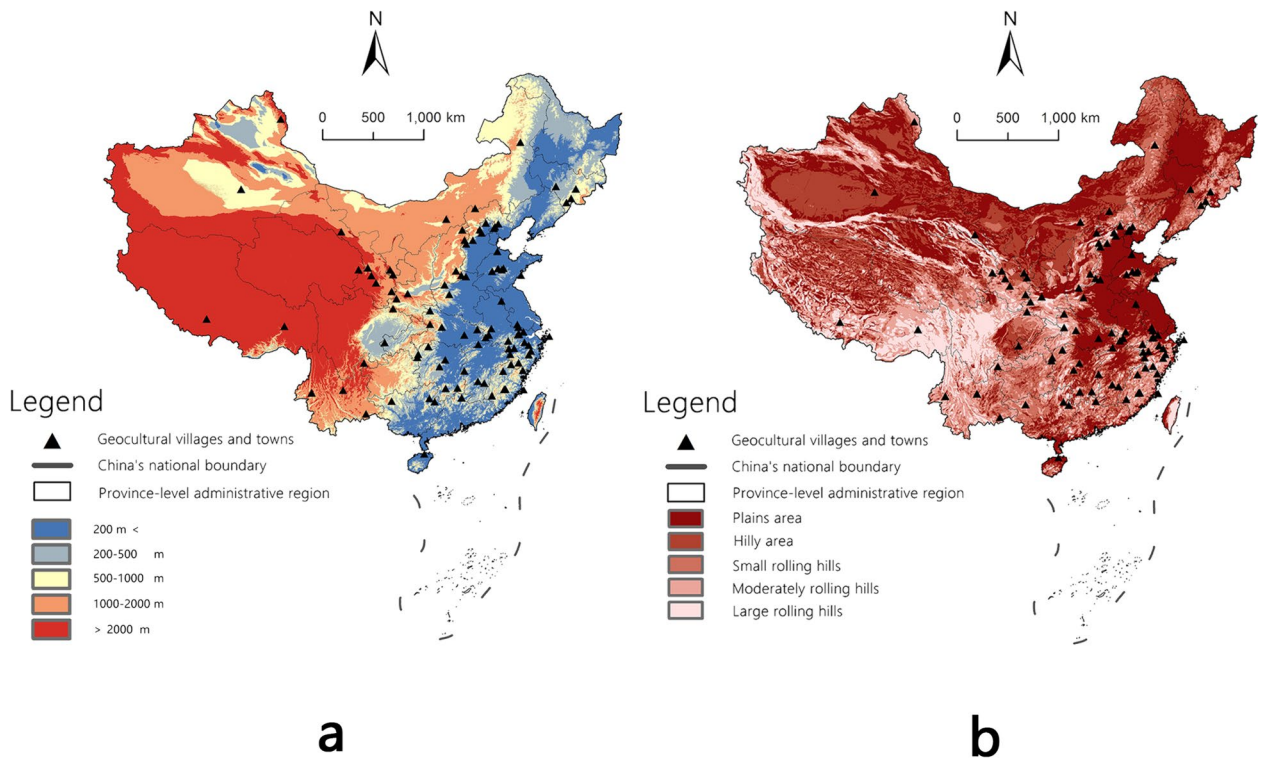


Fig. 6 **a** Elevation distribution of GCV(T)s in China. **b** Terrain distribution map of GCV(T)s in China

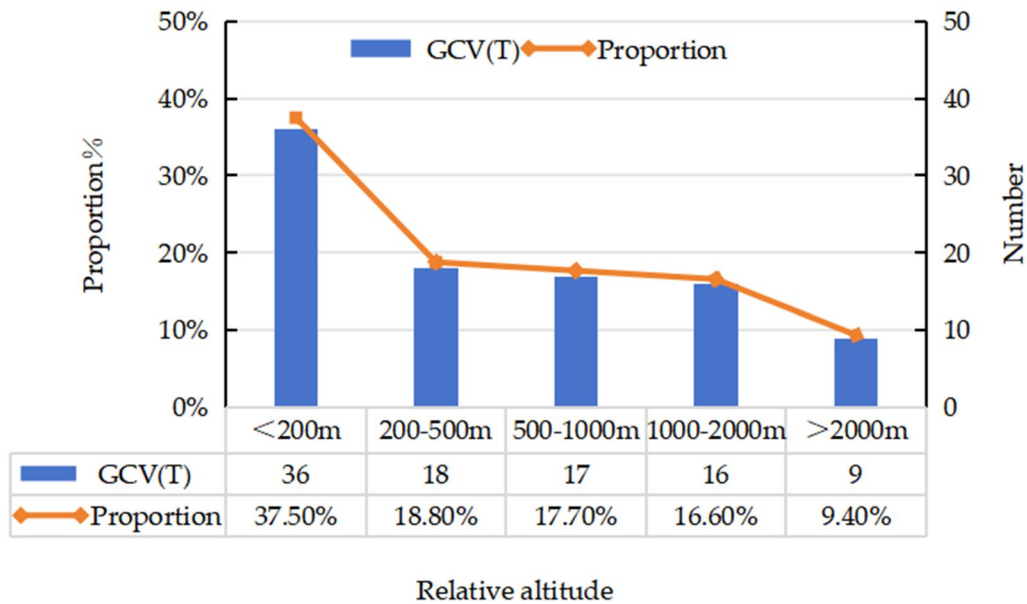


Fig. 7 The relationship between the number of GCV(T)s and relative elevation in China

natural conditions suitable for protection, development, and utilization. Moreover, vegetation manifests inherent ecological service functions, such as water conservation, soil and water conservation, and air purification. Hence,

the natural environment is harmonious and comfortable, and characteristic plant biological resources have become another influencing factor for site selection and GCV(T)s distribution. In this research, the spatial superposition

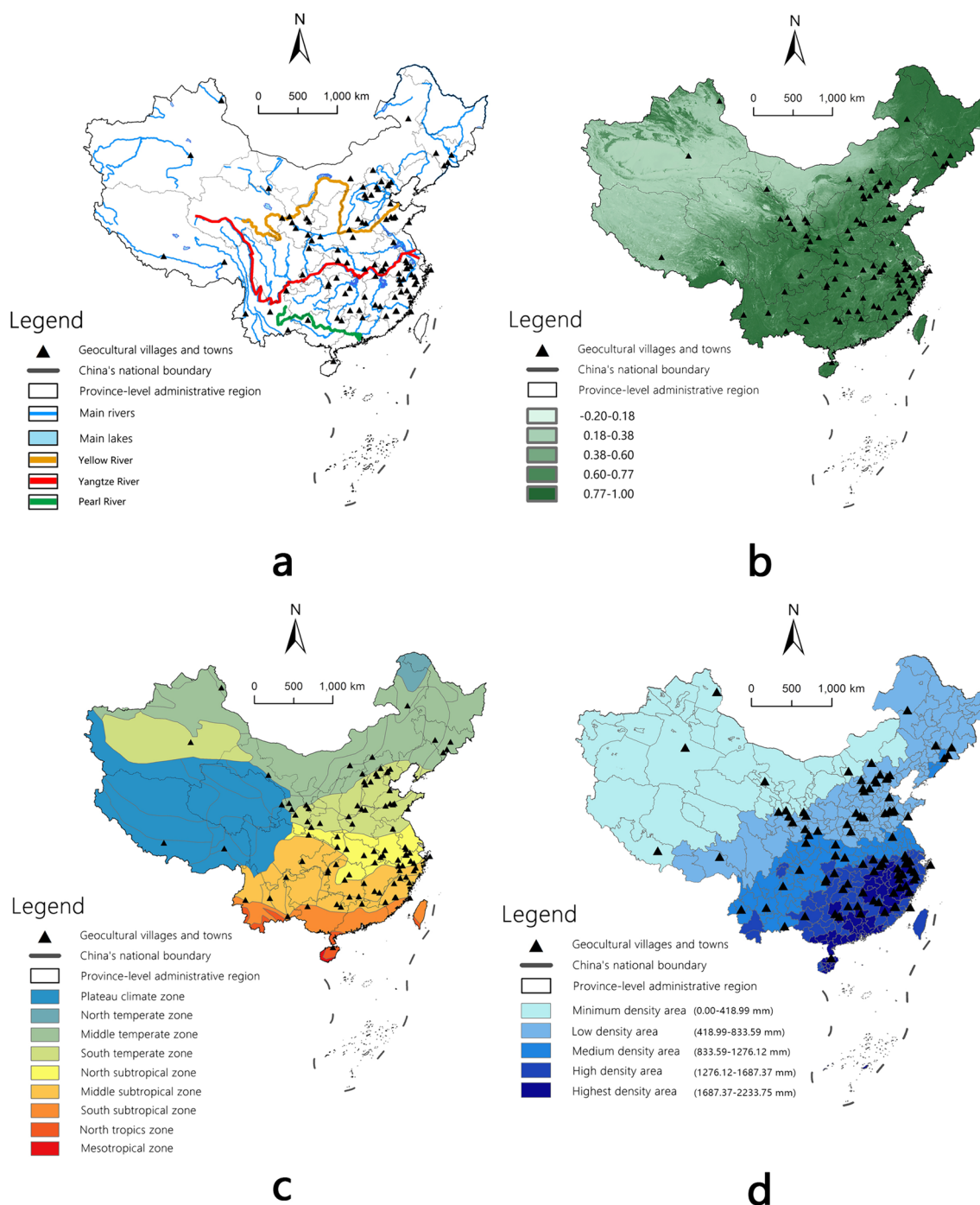


Fig. 8 Spatial relationships between the distribution of GCV(T)s and natural factors in China. **a** river systems **b** vegetation cover **c** climate systems **d** average rainfall

of GCV(T)s and Normalized Vegetation Index, which were classified into five classes using the natural segment point method, revealed that nearly 90% of GCV(T)s are located in areas with high vegetation indices, particularly in the southeastern forested region of China, exhibiting

obvious spatial agglomeration characteristics (Fig. 8). This indicates that the distribution of national GCV(T)s closely correlates with vegetation coverage. The high vegetation coverage around GCV(T)s reflected the respect and protection of the ecological environment

by the residents of GCV(T)s, and on the other hand, the better ecological environment further maintained the structural stability and functional diversity of the ecosystem around the villages, thus promoting and guaranteeing the sustainable development of GCV(T)s. The principal areas of national GCV(T)s distribution exhibit superior vegetation coverage, facilitating the use of vegetation resources in GCV(T)s through health tourism, recreation and sightseeing, leisure and vacation, science education, scientific research, and other activities.

Human resources conditions

Human resource conditions also constitute a crucial factor influencing the spatial distribution of GCV(T)s. By disclosing the coupling and mutual feedback relationships among the humanistic factors [84, 85], the interplay of multiple factors was analyzed in each dimension through the spatial superposition method (Fig. 9). We further examined the humanistic influence mechanisms of the 12 driving factors on the spatial distribution of GCV(T)s across the three dimensions: socioeconomics, tourism resources, and cultural resources. Table 4 exposes that the socioeconomic factors' influence on the spatial distribution of GCV(T)s is as follows: GDP (0.07) > population (0.06) > transportation (0.04) > city distance (0.03). The tourism resource factors' effects on the spatial distribution of GCV(T)s are as follows: A-level and above scenic spots (0.10) = traditional villages (0.10) > key tourism villages (0.06) > red tourist attractions (0.05). The emergence and development of GCV(T)s are inextricable from the local historical and cultural environment. The influence of cultural resource factors on the spatial distribution of GCV(T)s is as follows: cultural and related industries (0.1249) > historical and culturally famous towns and villages (0.0911) > cultural tourism expenditure (0.0266) > third industry expenditure (0.0041).

Overall, tourism resource factors exert a significant effect on the spatial distribution of GCV(T)s, with the q-values of A-level and above scenic spots and traditional villages being much larger than those of other driving factors.

The results of interaction detection depicted in Fig. 9 demonstrate that socioeconomic factors, tourism resources, and cultural factors exhibit nonlinear enhancing effects on the spatial distribution of GCV(T)s (Fig. 10). This indicates that human interactions with society, economy, tourism, history, and culture exert a significant influence on the specific arrangement of GCV(T)s. The explanatory power of the interacting drivers with other factor tests surpassed that of single-factor differentiation tests, highlighting a synergistic

effect among the factors. As evidenced by the interaction detection results in Fig. 10, the top 5 combinations of interaction detection effects are (X2)∩(X6) (0.33), (X2)∩(X5) (0.28), (X1)∩(X2) (0.27), (X5)∩(X8) (0.27), and (X2)∩(X8) (0.26). Among these, the interaction involving GDP and other factors displays the strongest effect, whereas the interaction between physical geography factors and historical and cultural factors exhibits the weakest effect. The explanatory power of most factors is < 0.25, suggesting that humanistic factors, rather than geological resources and natural conditions, primarily influence the spatial distribution of GCV(T)s.

Discussion

The spatial distribution pattern of GCV(T)s in China was analyzed using GIS. The development of GCV(T)s in China exhibits spatial unevenness and clustering, with considerable spatial distribution imbalance, particularly favoring the eastern region over the western region. A decreasing trend in the overall number of GCV(T)s is observed from the southeast coastal area to the northwest inland area. All regions should prioritize the protection and rational development of geological heritage to promote sustainable GCV(T) development. Various types of geological heritage contribute to regional variations in GCV(T) construction modes, leading to distinctive regional GCV(T) development characteristics. Consequently, planning and construction efforts for GCV(T)s should emphasize geological and cultural diversity, leverage tourism resources and cultural advantages of different regions, and foster sustainable development.

Based on the spatial distribution of GCV(T)s, coupling and mutual feedback analyses were conducted on geological heritage, the natural environment, and socioeconomic, historical, and cultural factors [86]. Geological heritage is a primary determinant influencing GCV(T) spatial distribution, reflecting geological characteristics and imposing constraints. In Baiyankeng village, located in Zhejiang Province, heightened awareness of geological preservation, particularly regarding numerous geological heritage sites below the provincial level, has facilitated increased emphasis on conservation and utilization efforts. This heightened focus has resulted in environmental enhancements, local development stimulation, and enhanced preservation and dissemination of geological culture, consequently contributing to a sustained rise in the populace's happiness index [87–89]. Geoconservation assumes an increasingly pivotal role in GeoConservation Values (Tourism) development. Natural environmental factors play a secondary role in spatial distribution of GCV(T)s. While natural

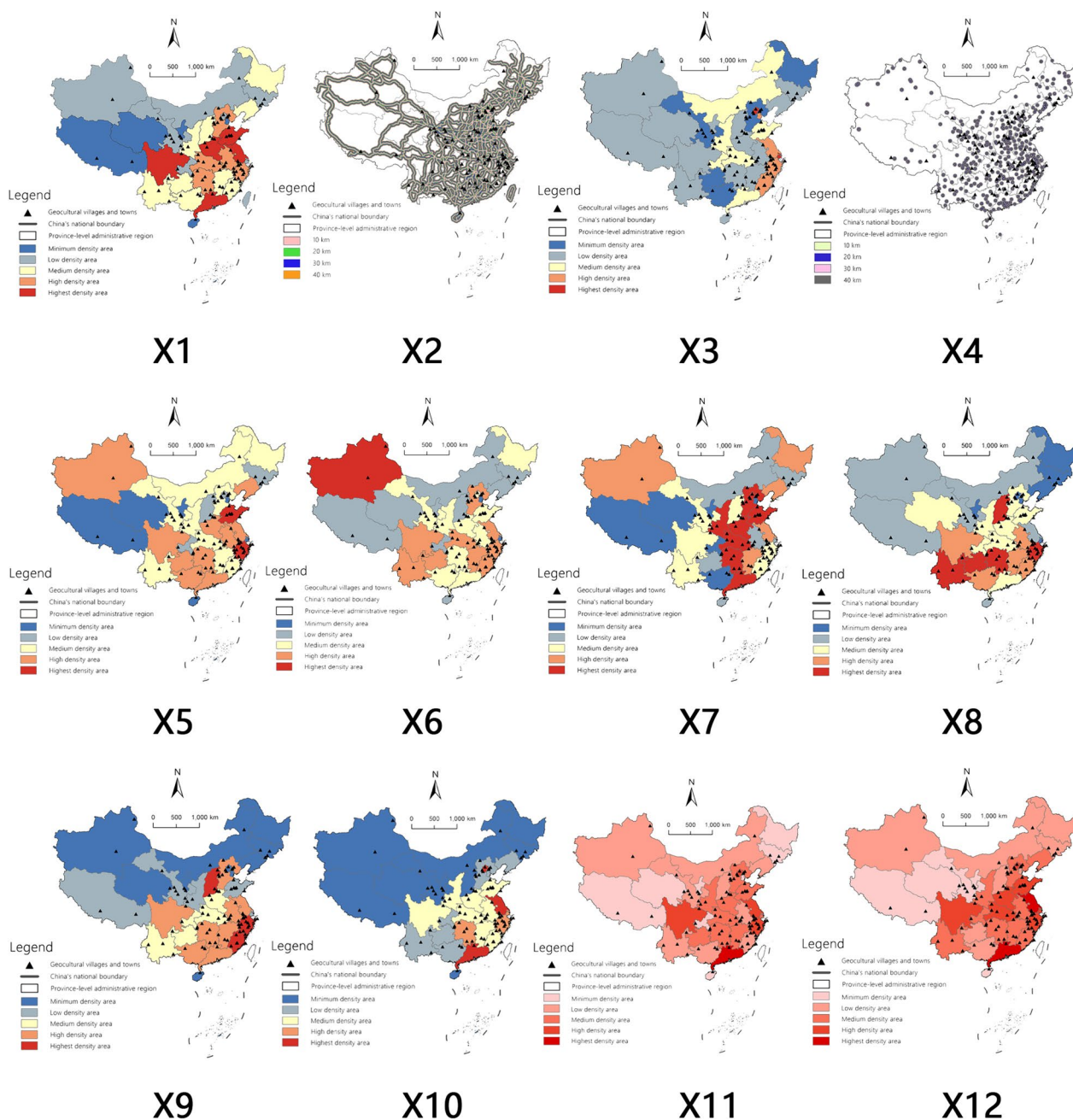


Fig. 9 Spatial coupling with GCV(T)s between multiple influences and its superposition analysis

environmental elements play a subsidiary role in the distribution of GCV(T)s, variations in geographical settings precipitate distinct distributions of such sites. Noteworthy is the clustering of certain region-specific GCV(T)s in the western regions, while the majority are concentrated in low-lying plains and hilly terrains with ample precipitation and verdant vegetation. The favorable climatic conditions in these areas support agricultural activities, thereby enabling the design of

integrated projects merging agriculture and tourism, such as geology+eco-tourism and geology+eco-agriculture. Within the realms of farming and community life, the establishment of geo-agricultural cultural tourism attractions and recreational zones is feasible [90]. Conversely, GCV(T)s positioned in high-altitude, arid regions encounter challenges associated with limited tourism demand, sparse populations, and inadequate transportation infrastructure. Local

Table 4 Human factors affecting the spatial distribution of GCV(T)s in China

Indicator dimensions	Detection factors	Data source	Q-value
Socioeconomics	Population(X1)	Official statistics	0.06
	Distance from highway(X2)	ArcGIS processing data	0.04
	GDP per capita(X3)	Official statistics	0.07
	Distance from central city(X4)	ArcGIS processing data	0.03
Tourism resources	Number of A-level and above scenic spots(X5)	Official statistics	0.10
	Number of red tourist attractions(X6)	Official statistics	0.05
	Number of key tourism villages(X7)	Official statistics	0.06
	Number of traditional villages(X8)	Official statistics	0.10
Culture resources	Number of historical and culturally famous towns and villages (X9)	Official statistics	0.07
	Number of cultural and related industries(X10)	Official statistics	0.08
	Cultural tourism expenditure(X11)	Official statistics	0.07
	Third industry expenditure(X12)	Official statistics	0.06

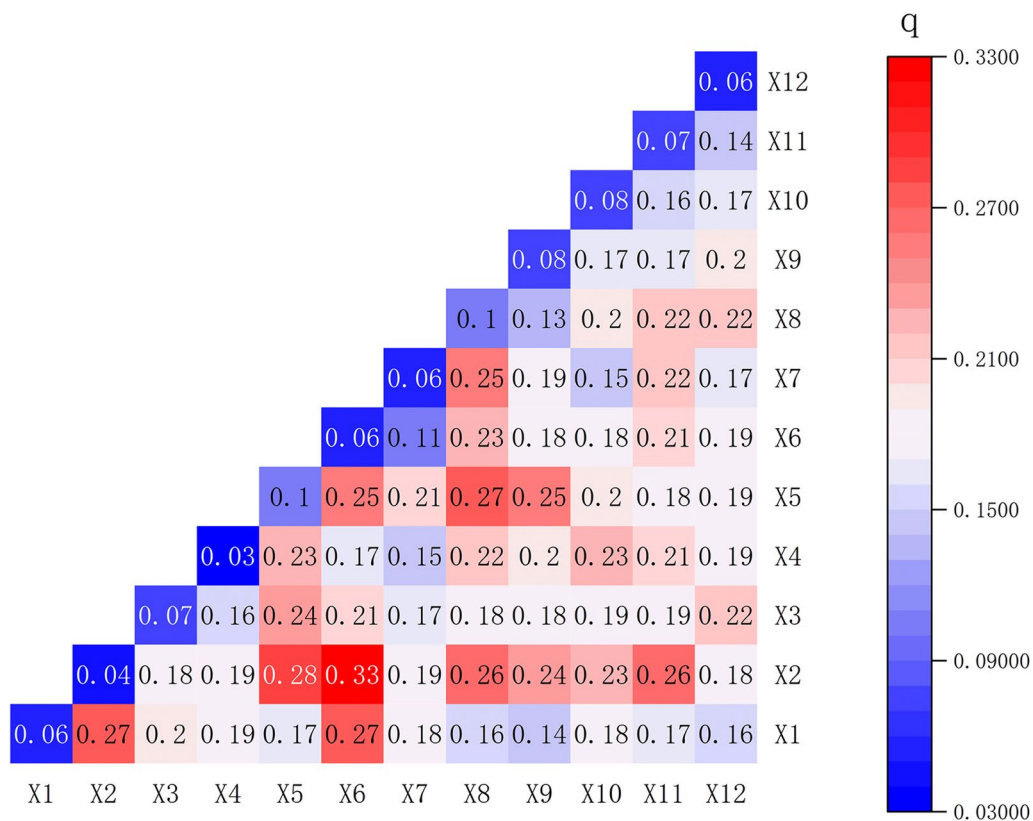


Fig. 10 Interaction detection results between multiple influences

government can bolster financial investment, tourism marketing, and tourist influx through holiday packages to enhance public amenities. Human influences significantly shape the spatial dispersion of GCV(T)s, with economic growth, tourism resources, cultural

legacy, and policy formulation serving as critical research domains.

Geo-detector analyses indicate that socioeconomic factors, tourism assets, and historical-cultural facets underpin the emergence and progression of GCV(T)s.

Spatially, except for certain region-specific clusters in the western regions, the majority of GCV(T)s are situated in the middle and lower reaches of the Yellow River and Yangtze River, characterized by robust economic activity and efficient transport networks. Cultural tourism resources are pivotal in shaping the spatial distribution of GCV(T)s, intertwined with local cultural ambiance in fostering cultural tourism emergence. Areas rich in tourism assets and deep-rooted cultural legacies are more conducive to the genesis of GCV(T)s, with governmental involvement pivotal in nurturing, overseeing, and regulating these endeavors [91–93]. Regions boasting enriched cultural environments offer fertile ground for GCV(T)s construction and evolution. A-class scenic locales, national historical and cultural towns and villages, traditional villages, and culture-related industries exert substantial influence on GCV(T)s spatial distribution, with the synergy of dual factors wielding greater impact than individual influences.

Consequently, when appraising factors dictating GCV(T)s spatial dispersion, primacy should be accorded to geological heritage, geographical location, and environmental attributes, alongside historical-cultural worth, urban development plans, societal requisites, market potential, technical–economic viability, cultural safeguarding strategies, and social awareness [94]. These factors mold the layout and establishment models of GCV(T)s to foster symbiotic growth between GCV(T)s construction and urban development. China's GCV(T)s are endowed with abundant geological resources, rich cultural heritage, unique historical and cultural value, scientific research and educational significance, economic tourism value, and natural landscape resources. By safeguarding geological culture, China can preserve its natural resources and heritage while transmitting valuable cultural history [95]. Tailored protection priorities and policies should be established for different types of GCV(T)s [96, 97]. Villages rich in geological resources require increased geological heritage protection, infrastructure enhancement, and vigorous tourism development [98–100]. GCV(T)s rich in human resources necessitate heightened historical and cultural promotion, alongside a focus on preserving the original appearance of villages and towns. Environmental considerations are crucial to prevent overcommercialization and loss of characteristics for GCV(T)s near urban areas. In remote regions such as Tibet and Xinjiang, increased policy and financial investment is essential to protect and develop GCV(T)s, improve livelihoods, and enhance resident development capacity [101].

GCV(T)s face various challenges related to geological resource utilization, cultural preservation and

inheritance, and modernizing village construction. Governmental policies and strategies play a significant role in shaping the spatial distribution of GCV(T)s in China, primarily driven by political influences. The establishment of robust government policies focusing on the protection of GCV(T)s and the promotion of sustainable development is crucial. Strategies encompassing environmental monitoring, judicious development planning, conservation tactics to preserve unique cultural heritage, local cultural educational initiatives, and the promotion of sustainable tourism for economic growth, significantly impact the distribution of GCV(T)s to diverse extents. Consequently, the government could consider establishing a dedicated GCV(T) protection system and a specialized department for geological preservation and village development. In conclusion, achieving sustainable and high-quality development of GCV(T)s requires concerted efforts and measures from various stakeholders. Government, enterprises, and residents should collaborate to integrate GCV(T) development with geoheritage protection, rural tourism development, and cultural industry promotion. Heightened attention to geological heritage protection, environmental improvement, cultural inheritance and promotion, and local economic development has led to increased public happiness. Significantly, the development of GCV(T)s has unfolded novel avenues for geological heritage protection, representing an innovative approach that transcends conventional methods such as the establishment of geoparks and nature reserves in China. Sustainable development initiatives undertaken in GCV(T)s yield significant economic advantages, primarily by stimulating rural tourism and bolstering the local economy. GCV(T)s harbor distinct cultural and natural resources that draw in tourists in pursuit of authentic experiences. The implementation of sustainable practices can amplify the allure of these attractions, thus fostering tourism. Research suggests that the evolution of sustainable tourism in rural areas not only elevates tourist counts but also extends their durations of stay, culminating in augmented expenditures and heightened economic profits for local communities [102]. For example, in locales such as Salamanca, Spain, endeavors towards sustainable tourism have facilitated employment for local guides, artisans, and farmers, thereby aiding in poverty reduction and promoting economic acceleration in proximate regions [103]. Moreover, sustainable development undertakings in GCV(T)s have conserved traditional industries such as handicrafts, arts, and agriculture, thereby generating both direct and indirect employment possibilities. The recognition of Hongcun villages in Anhui Province, China, as UNESCO World Heritage Sites notably augmented the number of visitors

and revenues, all the while maintaining their authenticity and bolstering local livelihoods [104]. Conservation and sustainable development endeavors also amplify the attraction of GCV(T)s to both investors and residents. Advancements in infrastructure coupled with the preservation of historical edifices have the potential to heighten property values and captivate investments in hospitality and tourism-related amenities [105]. In conclusion, sustainable development strategies achieve two primary goals: the preservation of geocultural heritage and the stimulation of economic growth, accomplishing these by enhancing rural tourism and diversifying the local economy of GCV(T)s.

Prior researches employing GIS analysis and mathematical modeling to explore the spatial patterns of traditional villages have garnered significant findings, primarily regarding the regional spatial distribution of these villages and the determinants impacting them [58–61]. Given that GCV(T)s also manifest as traditional villages, commonalities exist between the outcomes of this study and the spatial distribution patterns of traditional villages across the nation, along with the factors influencing them. Nonetheless, the influence mechanism driving the spatial distribution of GCV(T)s diverges significantly from that of traditional villages, as well as tourism-oriented villages and towns. Consequently, this study employs GIS spatial analysis and mathematical statistics to investigate the spatial distribution traits and influencing factors of GCV(T)s in China on a nationwide scale, thereby offering theoretical underpinning for their preservation and development.

For greater clarity and to address the reviewer's concerns, a section detailing future research directions has been incorporated, with the revised content as follows: Nonetheless, with the continuation of national trends such as urbanization, climate change, and the evolution of tourism patterns, there emerges an increasing necessity for extended research to ameliorate the conservation and management of GCV(T)s. It is of paramount importance to devise effective strategies that amalgamate geo-cultural heritage with sustainable tourism practices, whilst preserving authenticity and local identity. Furthermore, evaluating the susceptibility of GCV(T)s to climate change and formulating adaption strategies is integral to their enduring sustainability. The focus of research endeavors should be on climate resilience planning, sustainable land-use practices, and formulating strategies to alleviate environmental impacts on these communities. These measures are imperative for the protection of the unique heritage and the promotion of sustainable development of GCV(T)s.

Conclusion

In this study, spatial analysis is conducted using GIS and mathematical statistics. The results reveal an uneven yet cohesive spatial distribution pattern of GCV(T)s in China, characterized by large agglomerations and small dispersions, influenced by the geographical environment. A high-density agglomeration area is formed, with the Yangtze River Delta and Beijing-Tianjin-Hebei region as the core, encompassing 85.42% of the total area. The spatial distribution pattern of GCV(T)s is affected by multiple factors, including geological, natural, and human factors. Geological factors such as active geological structures, abundant geologic relic resources, high elevations, and low topographic relief are correlated with GCV(T)s distributions, predominantly situated in areas with ample rainfall. Natural factors, including abundant rainfall, good vegetation cover, and proximity to rivers and lakes, also influence the distribution. Additionally, human factors, such as social development level, regional tourism resources, and cultural resources, play a role in shaping the spatial distribution pattern of GCV(T)s, reflecting integrated and homogeneous effects.

Drawing on the spatial differentiation characteristics and influencing factors of GCV(T)s in China, sustainable development recommendations are proposed to address regional distribution imbalances, diversify geo-cultural types, and achieve multidirectional coordination. Future GCV(T)s development should explore varied construction modes, implement tailored protection strategies for different types of geoheritage resources, and realize coordinated sustainable regional and development. Simultaneously, the strategic development level of GCV(T)s should be enhanced to strike a balance between geoheritage protection and economic development, thereby achieving high-quality development of the GCV(T) region.

In conclusion, this study effectively elucidates the spatial distribution characteristics and influencing factors of GCV(T)s, offering research insights for quantitatively investigating their spatial differentiation in China. It forms the basis for policy formulation to promote balanced and sustainable regional economic development, rational geoheritage development, and the sustainable development of GCV(T)s.

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

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Author contributions

ZY (Yunxing Zhang, first author): conceptualization, methodology, software, formal analysis; ZZ (Zhenyu Zhang): writing—original draft, data curation; data curation; software, formal analysis; LC (Chenchen Lu): writing review and editing, data curation; YM (Meiyu Yang): software, writing—review and editing; ZY, GC (Yunxing Zhang, Cuihua Gu, corresponding author): resources, supervision, review, project administration. All the authors have read and approved the final manuscript.

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Availability of data and materials

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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