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Influence of human settlements factors on the spatial distribution patterns of traditional villages in Liaoning province

Guiqiao Tao[1,2], Xueming Li[1,2,3,4,5], Shenzhen Tian [1,2,3,4,5✉], Hang Li[1,2] & Yishan Song[1,2]

Traditional villages embody China's long-standing farming culture and are the carriers for the inheritance and development of traditional culture in rural China. However, because of the continuous erosion of rural space due to China's rapid urbanization, traditional villages are gradually declining and even disappearing. Protecting traditional villages has become a significant scientific problem in the implementation of the "Rural Vitalization Strategy" in the new era. The study of the spatial distribution pattern of traditional villages and its influencing factors is an important basis for formulating macro-protection policies for traditional villages in China. However, the existing literature is one-sided and subjectivity in revealing the influencing factors, making it difficult to form accurate and comprehensive protection policies. Employing the Gini coefficient, kernel density estimation, and the Geographically Weighted Regression (GWR) model, this study analyzes the impact of human settlements factors on the spatial distribution patterns of traditional villages in Liaoning province. Results can be summated as follows. (1) The spatial distribution of traditional villages in Liaoning exhibits a clustered pattern. (2) In terms of the geographical regional scale, the distribution is highly uneven and mainly concentrated in the western region of Liaoning. At the municipal scale, the distribution is relatively uneven and primarily located in the cities of Chaoyang, Jinzhou, Huludao, Panjin, Anshan, and Dalian. (3) The majority of traditional villages are distributed along the southwest–northeast axis of the standard deviation ellipse, which corresponds with the main mountain ranges of Liaoning. (4) The distribution density features a western continuous clustering, central and eastern scattered clustering, and edge clustering pattern. (5) The spatial distribution patterns of traditional villages in Liaoning are influenced by various human settlements factors, with spatial variation in the nature and intensity of the effects of these factors. (6) The natural factors of human settlements are the dominant factors in the spatial distribution patterns of traditional villages, while the humanistic factors of human settlements have a dual impact on these patterns. This paper presents novel ideas for the study of the spatial distribution pattern of traditional villages, scientific support for the development of the disciplines of rural geography and the geography of human settlements, and new scientific decision-making and theoretical support for the protection and utilization of traditional villages.

A full list of author affiliations appears at the end of the paper.

Introduction

Traditional villages refer to early-established villages that possess abundant traditional resources and hold certain historical, cultural, scientific, artistic, social, and economic value. In view of such value, traditional villages need to be protected. (Hu et al., 2014) The proper utilization and conservation of traditional villages are crucial for promoting the implementation of China's "Rural Vitalization Strategy." However, with the rapid urbanization of China, urban elements continuously encroach upon traditional villages, precipitating a series of crises such as population hollowing, spatial fragmentation, production disorder, cultural disconnection, and ecological imbalance (Li et al., 2018), Or even disappear (Wang et al., 2021). These issues have garnered significant attention from the Chinese government. Since 2012, in response to the policy document, *CPC Central Committee State Council Several Comments on Accelerating the Development of Contemporary Agriculture and Further Invigorating Rural Development*, the Ministry of Housing and Urban-Rural Development and other departments have jointly approved and published six lists of traditional Chinese villages, identifying some 8,155 such villages in the country. This has significantly enhanced the conservation practice of traditional villages and related scientific research. However, scholars have observed that the focus on individual conservation for traditional villages, centered on the "Conservation List," has overlooked the interconnections between traditional and neighboring villages in terms of natural ecology and human resources throughout their historical development, and is incapable of fully and systematically showcasing the regional characteristics of local distinctive culture, potentially leading to unforeseen cultural destruction and loss (Chang and Hu, 2020). Therefore, in 2022, the No. 1 document of the central government, *CPC Central Committee State Council Comments on Doing a Good Job of Comprehensively Promoting the Key Work of Rural Revitalization in 2022*, further advocates the implementation of centralized and contiguous protection and utilization of traditional villages. It is evident that the protection and utilization of traditional villages must evolve from individual village to regional groups; thus, determining how to scientifically analyze the spatial distribution patterns of traditional villages based on zoning, explore its influencing factors based on multi-source data synthesis, and devise targeted protection strategies has become an urgent scientific issue.

To promote the conservation and development of significant non-renewable cultural heritage sites, international scholars have conducted extensive research from different perspectives, such as from that of heritage value, rural archaeology, rural art, rural vitality, architectural and spatial layout, risk for disaster, tourism development, organic renewal, and protected models, with significant achievements (Table 1). However, the review of the existing research literature reveals that past academic achievements of foreign countries have primarily focused on the meso- and micro-levels, such as village clusters or individual village within a small area, with an emphasis on qualitative interpretation and individual case analysis. In recent years, Chinese scholars have shown a marked interest in employing geospatial analysis techniques to explore the spatial distribution patterns of traditional villages on a large scale and their influencing factors, and to propose corresponding conservation strategies at a macro level. Given China's vast land area, complex geographic environment, and high number of traditional villages, this approach is both necessary and effective. It facilitates the promotion of China's strategy for the centralized and contiguous protection and utilization of traditional villages and also serves as a reference for the rest of the world in exploring the protection modes of traditional villages at a macro scale. This constitutes one of the motives of this study.

The spatial distribution pattern of traditional villages is the primary research topic. Academics usually use mathematical and statistical methods such as the nearest neighbor index, geographic concentration index, imbalance index, or spatial Gini coefficient to analyze the spatial distribution pattern of traditional villages in national, regional, provincial, municipal, or special geographic zones, such as natural areas, cultural zones, and economic zones (Table 2). They then recommend zoning protection policies based on the concentration degree of the spatial distribution, which has had a positive effect as regards practical application. There are research cases in East China, South China, North China, Central China, Southwest China, and Northwest China; however, a lack of research cases in Northeast China hinders the completeness of the literature. Liaoning Province, as a representative province of Northeast China, is one of the regions with the most serious economic downturn, population loss, and hollowing out of the countryside, and also one of the regions with the most prominent pressure on the protection of traditional villages. Hence, it is of typical case significance to carry out targeted and specific research on it, which is another motivation for this study.

The influencing factors of the spatial distribution pattern of traditional villages are another important research topic. Currently, related studies: (1) with regard to raw data sources, most rely on the National Geomatics Center of China, local histories, ancient books, scientific research websites, and statistical yearbooks; (2) with regard to the composition of influencing factors, some employ a single factor such as rivers or traffic, while others use various combinations of factors such as elevation, slope, rivers, vegetation, economy, population, and traffic; (3) with regard to data analysis, some apply traditional ArcGIS spatial overlay techniques and statistical methods, while others utilize new geographic models such as Geographic Weighted Regression and Geographic Detector (Table 3). Although the aforementioned studies have met their intended objectives and scholars have proposed targeted protection recommendations based on their findings, it is important to note that: (1) existing studies either analyze a single factor or a combination of a few factors, which is one-sided and subjectivity, making it challenging to fully uncover the underlying reasons for the spatial distribution patterns of

Research theme	Case country	References
Heritage value	Spain	Soler-Estrela (2018)
	Indonesia	Bura and Ando (2023)
	Greece	Katapidi (2021)
	Republic of Korea	Kweon and Youn (2021)
	Japan	Chen and Nakama (2010)
Rural archaeology	Austria	Roland et al. (2022)
Rural art	Indonesia	Indra Wirawan (2022)
Rural vitality	China	Liu et al. (2023a)
Risk for disaster	Japan	Li et al. (2019)
Architectural and spatial layout	Saudi Arabia	Mohammed (2022)
	Turkey	Salgın et al. (2017)
	Italy	Ruggiero et al. (2019)
Tourism development	Indonesia	Dewia (2014); Ruhimat et al. (2018)
	Uganda	Lepp (2008)
	Botswana	Mbaiwa and Sakuze (2009)
	China	Gao and Wu (2017)
Organic renewal	China	Li et al. (2024a)
Protected mode	England	Pendlebury (1999)

Table 1 Typical literature on the protection and utilization of traditional villages in the world.

Table 2 Typical literatures on spatial distribution pattern of traditional villages at different geographical scales.

research scale		research method	References
Nationwide		Standard Deviation Ellipse, spatial autocorrelation analysis	Chen et al. (2023b)
Tibetan Plateau (Natural zone)		Nearest Neighbor Index, Kernel Density Estimation Method, spatial autocorrelation analysis	Jin et al. (2022)
Jiangnan (Cultural zone)		Nearest Neighbor Index, Kernel Density Estimation Method, spatial autocorrelation analysis	Bi et al. (2024)
Central Plains economic zone		Kernel Density Estimation Method, spatial autocorrelation analysis	Guan et al. (2017)
Eastern China	Fujian Province	Geographical concentration index, Imbalance index, spatial autocorrelation analysis, Kernel Density Estimation Method	Ma et al. (2024)
South China	Gudong Province	Nearest Neighbor Index, Gini Coefficient, Imbalance index	Feng et al. (2017)
North China	Shandong Province	Moreland index, Standard Deviation Ellipse, Kernel Density Estimation Method	Li et al. (2024b)
	Qingdao City	Nearest Neighbor Index, Moreland index, Kernel Density Estimation Method	Zhang et al. (2020)
Central China	Henan Province	Nearest Neighbor Index, Gini Coefficient, Kernel Density Estimation Method	Liu et al. (2023b)
	Hunan Province	Standard Deviation Ellipse, Kernel Density Estimation Method	Liu et al. (2024)
Southwest China		Kernel Density Estimation Method	Ma and Tong (2022)
Northwest China		Nearest Neighbor Index, Kernel Density Estimation Method, spatial autocorrelation analysis	Huang et al. (2021)

traditional villages, and consequently difficult to develop accurate and comprehensive macro-protection policies; (2) additionally, many studies rely on traditional statistical yearbooks, with remote sensing data—such as the normalized difference vegetation index (NDVI) and night lighting index, which objectively reflect natural and economic conditions—rarely utilized, thereby diminishing the objectivity of the analysis results to some extent. Therefore, effectively utilizing multi-source data to construct a relatively integrated and dynamic system of influencing factors has become an urgent issue.

To address the above issues, this study introduces the sciences of human settlements. Human settlements refer to the territorial arrangements made by human beings as a result of human activities, and their main purpose is to satisfy the needs of human survival (Doxiadis, 1975). The sciences of human settlements originated from the theory of "science of human settlements" proposed by the Greek scholar C. A. Doxiadis in the 1950s, which was then introduced into China in the 1990s by academician Wu Liangyong in line with the Chinese characteristics of the development of its theoretical connotation and application of practice. Human settlements include five levels: global, national and regional, urban, community (neighborhood), and architectural; and five systems: natural, human, social, residential, and supportive in terms of content (Wu, 2001). The sciences of human settlements advocate the systematic study of the human living environment considering both natural and human aspects. As representative human settlements, traditional villages can better understand their spatial distribution patterns with the help of systematic thinking of the sciences of human settlements.

In view of the foregoing, this study uses Liaoning Province as an example, constructing a geospatial multi-source database on the distribution of traditional villages and human settlements factors. It comprehensively utilizes the nearest neighbor index, the Gini coefficient, the standard deviation ellipse, and the kernel density estimation method to characterize the spatial distribution pattern of traditional villages, and employs the "Grid analysis method – OLS model – GWR model" to analyze the degree and spatial differences in the influence of each human settlements factor on the spatial distribution pattern, and accordingly formulates targeted protection strategies. This study aims to provide scientific support for the development of rural geography and geography of human settlements, offering theoretical support for the protection and utilization of traditional villages in Liaoning Province, and supplying a reference method for exploring the protection mode of traditional villages from a macroscopic scale in other regions of China and even globally.

Data and methods

Study area. Liaoning is a province located in the southern part of northeastern China, between 118°53' E to 125°46' E and 38°43' N to 43°26' N. The total land area is 148,600 km², accounting for 1.5% of the national land area. The terrain is high in the north and low in the south, with mountains and hills on the eastern and westerns sides and plains in the middle, approximating to roughly 60% mountainous area, 10% water, and 30% arable fields. It has abundant sunshine and a continental monsoon climate, with precipitation and heat occurring in the same season. Liaoning is a key production area for agricultural and livestock products in China. Abbreviated as Liao, Liaoning has a long history, with the Niuheliang Hongshan Cultural site in Chaoyang dating back some 5000 years and constituting part of the origins of Chinese civilization. This study's research targets comprised the 78 traditional villages in Liaoning, including 45 national traditional villages identified by the Ministry of Housing and Urban-Rural Development (8 in the third batch, 9 in the fourth batch, 13 in the fifth batch, and 15 in the sixth batch) and 33 provincial traditional villages demarcated by the Department of Housing and Urban-Rural Development of Liaoning (Fig. 1).

Model construction and data sources. Regional human settlements are complex, extensive, and consist of multiple factors. Generally, factors can be divided into two categories: natural and humanistic factors. (Yang and Zhang, 2016) Natural factors do not change according to human subjective will and are objective conditions that restrict regional human settlements. Of the many natural factors that affect human settlements, fundamental and dominant factors include topographical, climatic, hydrological, and vegetation conditions. (Feng et al., 2008) Humanistic factors are the results of human activities and are subjective conditions that restrict regional human settlements. Many humanistic factors affect human settlements, notably land cover, socioeconomic development, and transportation, all of which are closely related to human activities. (Guan et al., 2022) As traditional villages are a special type of cultural heritage, this study specifically includes regional cultural indicators. Natural factors of human settlements are the foundation for the creation of traditional villages, while humanistic factors are essential conditions for the development and preservation of traditional villages. the interaction between these factors shapes the spatial distribution patterns of traditional

Table 3 Typical literatures on influencing factors of spatial distribution pattern of traditional villages.

Influence factors		Data sources	Analytical methods	References
Single factor	River	National Geomatics Center of China	ArcGIS spatial overlay techniques and statistical methods	Xu et al. (2023)
	Ancient and present traffic	Local Chronicles, Ancient books, National Geomatics Center of China	ArcGIS spatial overlay techniques and statistical methods	Chen et al. (2020)
Multiple factors	Elevation, traffic, Economy	National Geomatics Center of China, Statistical yearbook	ArcGIS spatial overlay techniques and statistical methods	Li et al. (2015)
	Elevation, Slope, River, Vegetation, Economy, Population, traffic	Research website, Statistical yearbook	Geographic Detector	Chen et al. (2023a)
	Elevation, Vegetation, Cities, Population, Economy, traffic	National Geomatics Center of China, Statistical yearbook	Geographic Weighted Regression	Li et al (2020)

villages. Based on the above ideas, this study adopts a grid to extract the mean value of the kernel density of traditional villages (KDTV) in Liaoning Province. It adopts the standardized treatment of extreme deviation as the dependent variable and a grid to extract the mean value of each Human Settlements Index. It adopts the standardized treatment of extreme deviation as the independent variable to construct the OLS and GWR analysis models. The research framework of the article is shown in Fig. 2.

In the selection of independent variables, this study included four indices of natural factors: terrain ruggedness index (TRI), climate comfort index (CCI), hydrological index (HI), and NDVI and four indices of humanistic factors: land cover index (LCI), night light index (NLI), cultural density index (CDI), and traffic accessibility index (TAI).

More specifically, in the TRI, terrain ruggedness refers to the difference between the highest and lowest points in a specific area. Terrain ruggedness is one of the factors that lead to soil erosion and is an important factor limiting the development of the regional human settlements. In the CCI, climate comfort is a biometeorological indicator that measures the comfortableness of people under different meteorological conditions, directly reflecting the sensory comfort level of the regional human settlements. This study used the internationally accepted temperature-humidity index (THI) and wind chill index (K) to comprehensively reflect climate comfort. In respect to the HI, the quantity of water resources directly affects soil quality, vegetation growth, and industrial and agricultural production. The HI reflects the region's water resources, which provide crucial support for the foundation of a regional human settlements. Meanwhile, the NDVI comprehensively reflects the distribution of natural resources in a region, such as water resources and soil fertility. It represents the settlements' ability to regulate climate, improve air quality, and prevent soil erosion, making it an important indicator of the regional human settlements.

In respect to the humanistic factor indices, the LCI reflects the structure of land use and land cover conditions in the region, representing the relationship between humans and land and affecting the suitability of the regional human settlements. The NLI reflects the intensity of human activities in the region and represents the level of construction and socioeconomic development of the regional human settlements. The CDI reflects the richness of the regional culture, which depends on the region's social structure, history, and geographical background. Studies show that the ancient post roads in eastern Liaoning not only served postal functions but also acted as channels for regional trade, ethnic migration, cultural exchange, and the spread of ideas, and thus possess manifold cultural value. (Huo, 2019) Accordingly, this study used the density of ancient post roads in eastern Liaoning to reflect the cultural richness of Liaoning. Finally, transportation supports the flow of materials, information, and people in a region and is a fundamental condition for socioeconomic development. Therefore, the TAI is an important indicator reflecting the convenience of regional transportation. Table 4 resents the calculation methods and original data sources for this study's independent variables.

Methods
Methods for analyzing spatial distribution pattern
Nearest Neighbor Index: At the macro scale, traditional villages can be abstracted as point elements and their distribution type can be identified using the nearest neighbor index. (Tian, 2020) The calculation formulas are as follows:
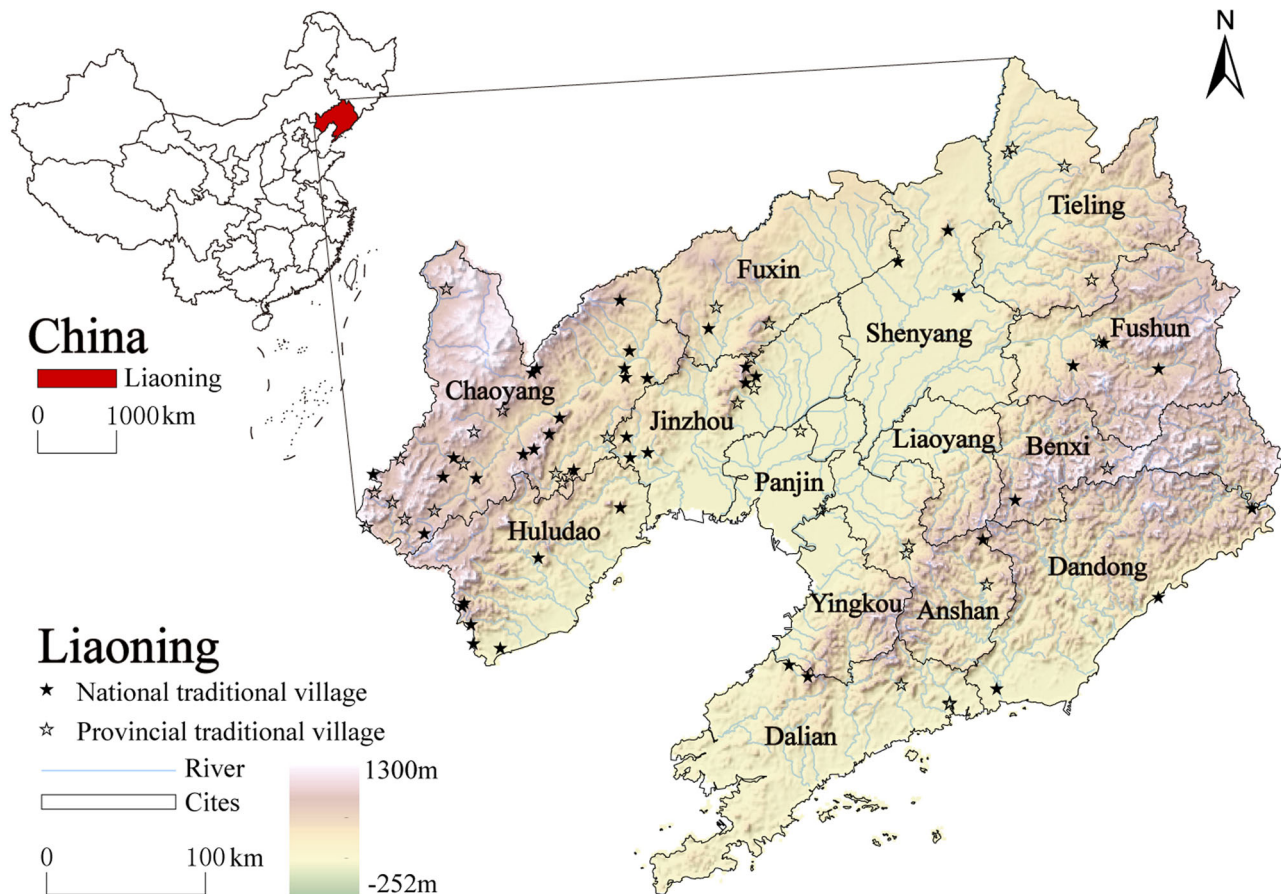
$$R = \frac{\bar{r}_1}{r_E} \tag{1}$$

Fig. 1 Distribution of traditional villages in Liaoning. This distribution map was developed by the authors using ArcGIS 10.8. The background map was published by the Ministry of Natural Resources of the People's Republic of China (drawing review No. GS (2019) 1821), available online at http://bzdt.ch. mnr.gov.cn/.

$$\bar{r}_1 = \frac{1}{n}\sum_{i=1}^{n} r_i \qquad (2)$$

$$r_E = \frac{1}{2\sqrt{n/s}} \qquad (3)$$

where R is the nearest neighbor index, $\bar{r}_1$ is the average observed distance, r_E is the expected average distance, r_i is the distance between a traditional village and its nearest traditional village, n is the number of traditional villages, and s is the area of the researched region. When $R > 1$, traditional villages tend to be evenly distributed; when $R = 1$, traditional villages are randomly distributed; when $R < 1$, traditional villages tend to be clustered.

Gini coefficient: The Gini coefficient can objectively determine the degree of clustering in the spatial distribution of geographical elements by comparing two sets of data. (Xu, 2014) Therefore, the Gini coefficient can be used to evaluate the regional distribution equality of traditional villages in Liaoning. The calculation formulas are as follows:

$$G = 1 - \sum_{i=1}^{n} a_i\big(2Q_i - v_i\big) \qquad (4)$$

$$Q_i = \sum_{k=1}^{i} v_k \qquad (5)$$

where G is the Gini coefficient, v_i is the proportion of the number of traditional villages in the ith region to the total village number

in the province, a_i is the proportion of the area of the ith region to the total area of the province, and Q_i represents the cumulative proportion of traditional villages from the 1st region to the kth region. The Gini coefficient ranges from 0 to 1, where G < 0.2 indicates a highly even distribution, $0.2 \leq G < 0.3$ indicates a moderately even distribution, $0.3 \leq G < 0.4$ indicates a relatively even distribution, $0.4 \leq G < 0.5$ indicates a relatively uneven distribution, $0.5 \leq G < 0.6$ indicates moderately uneven distribution, and G > 0.6 indicates highly uneven distribution.

Standard deviation ellipse: The standard deviation ellipse method characterizes the spatial distribution pattern of the geographical elements—including range, centroid, dispersion degree, clustering trend, and directional trend—by calculating parameters such as the area, centroid position, flatness, and rotation angle of the standard deviation ellipse. (Wu et al., 2023).

Kernel density estimation method: The kernel density estimation method calculates the distribution density of point elements within a certain area to explore spatial hot spots. It can be used to present the clustered areas of traditional village distribution. (Li et al., 2020) The calculation formula is as follows:

$$D\big(x_i, y_i\big) = \frac{1}{ur}\sum_{i=1}^{u} k\left(\frac{d}{r}\right) \qquad (6)$$

where D(x_i, y_i) is the kernel density value at the spatial location (x_i, y_i), r is the search radius (bandwidth), u is the number of traditional villages within distance r from location (x_i, y_i), k
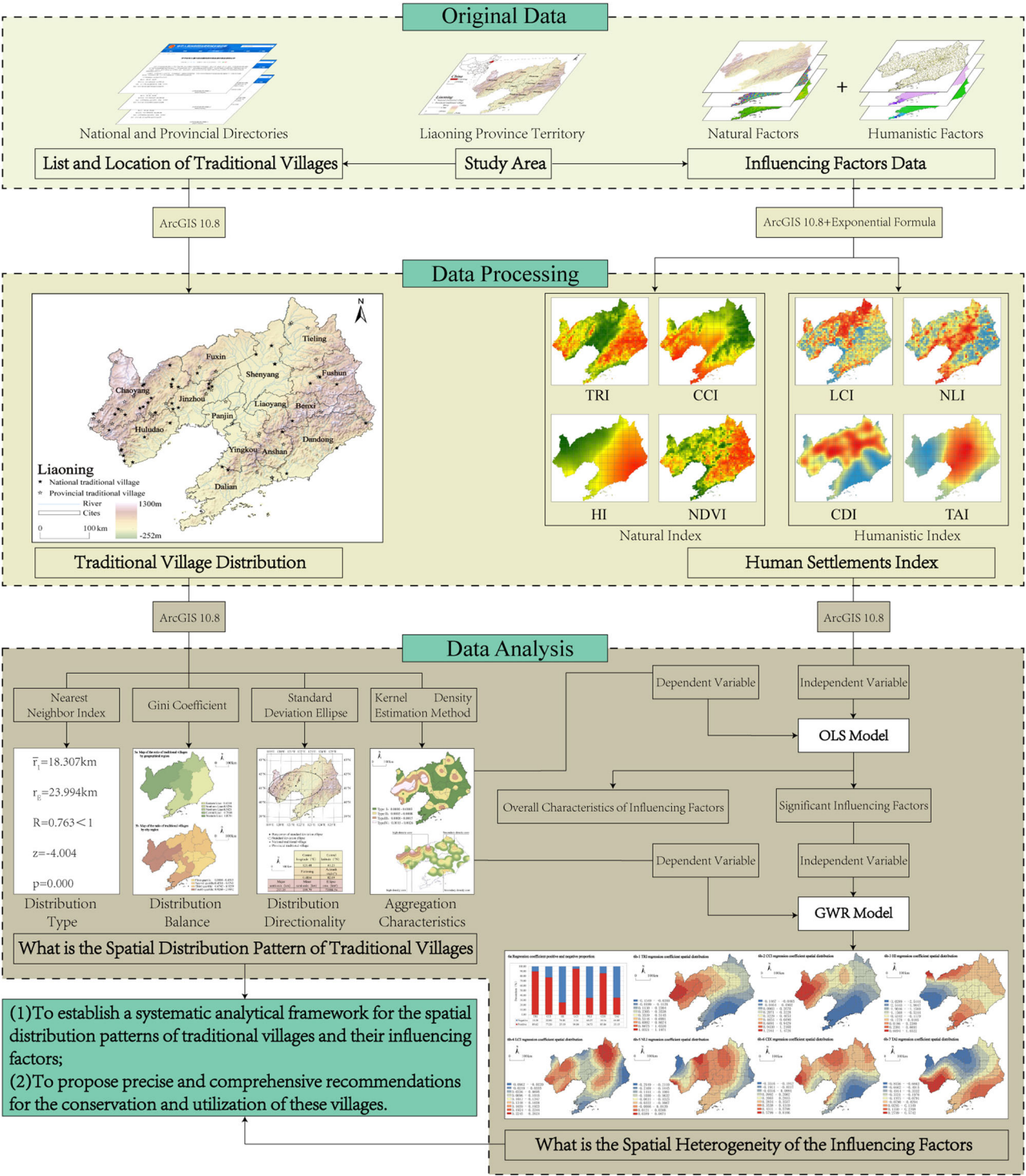
Fig. 2 Article research framework. This framework is divided into three levels, the first level is the data source, the second level is the data processing, the third level is the data analysis.

represents the spatial weighting function, and d is the distance between the current traditional village and (x_i, y_i).

Methods for analyzing influencing factors of spatial distribution patterns

Grid analysis method: The grid analysis method is a key technique for describing geographical spatial phenomena. It combines geographical spatial positioning and geographical feature expression, and has broad application prospects in spatial pattern analysis. (Wang and Wang, 2020) This study used the administrative boundaries of Liaoning as the base map, divided into 1667 grid units. To ensure the consistency of geographical element attributes within each grid unit, this study used a grid size of 10 km × 10 km.

GWR model: An extension of the OLS model, the GWR model incorporates geographical spatial coordinates into the analysis data, allowing for local estimation of parameters to explain the

Table 4 Calculation method of independent variable and sources of original data.

Variable	Calculation Method of Independent Variables	Source of Original Data
Y(KDTV)	Refer to formula (6)	Ministry of Housing and Urban-Rural Development https://www.mohurd.gov.cn/ Department of Housing and Urban-Rural Development of Liaoning https://zjt.ln.gov.cn/
X_1(TRI)	$TRI = E_{max} - E_{min}$ where TRI is the terrain ruggedness within a certain area, E_{max} is the maximum elevation value within a specific field, and E_{min} is the minimum elevation value within a specific field.	DEM data (ALOS 12.5 m) are sourced from the Resource and Environmental Science Data Registration and Publication System. https://www.resdc.cn/
X_2(CCI)	$THI = (1.8t + 32) - 0.55 \times (1 - f)(1.8t - 26)$ $K = -(10\sqrt{v} + 10.45 - v)(33 - t) + 8.55s$ where THI is the temperature-humidity index, K is the wind chill index, t is the annual average temperature (°C), f is the annual average relative humidity (%), v is the annual average wind speed (m/s), and s is the annual average sunshine duration (h/d). The climate comfort index is the normalized mean of THI and K.	Meteorological data such as temperature, relative humidity, wind speed, and sunshine duration (In order to obtain stable and regular meteorological data, the average data of the 1990s, 2000s and 2010s were used in this study, with a resolution of 1 km) are sourced from the Resource and Environmental Science Data Registration and Publication System. https://www.resdc.cn/
X_3(HI)	$HI = NAP \times \alpha + NWD \times \beta$ where HI is the hydrological index, NAP is the normalized precipitation, NWD is the normalized distance to water bodies, α is the weight of precipitation (set to 0.8), and β is the weight of distance to water bodies (set to 0.2). (see reference (Yang and Zhang, 2016) for the weights)	Precipitation data (averages from the 1990s, 2000s, and 2010s, with a resolution of 1 km) are sourced from the Resource and Environmental Science Data Registration and Publication System. Water vector data are sourced from the National Basic Geographic Information Center's 1:1,000,000 data. http://www.ngcc.cn/
X_4(NDVI)	——	The China Annual Vegetation Index (NDVI) spatial distribution dataset (2018, resolution 1 km) is sourced from the Resource and Environmental Science Data Registration and Publication System. https://www.resdc.cn/
X_5(LCI)	$LCI = LTi \times NDVI$ where LCI is the land cover index, LT_i is the weight of each land use type [see reference (Guan et al., 2022) for the weights], and $NDVI$ is the Normalized Difference Vegetation Index.	The China Multiperiod Land Use Remote Sensing Monitoring Dataset (CNLUCC, 2018, resolution 1 km) is sourced from the Resource and Environmental Science Data Registration and Publication System. https://www.resdc.cn/
X_6(NLI)	——	The China Annual Nighttime Light Dataset (2018, resolution 1 km) is sourced from the Resource and Environmental Science Data Registration and Publication System. https://www.resdc.cn/
X_7(CDI)	Refer to formula (6)	The linear vector data reflecting the cultural density of the ancient post roads in eastern Liaoning are drawn from the maps provided in reference. (Huo, 2019)
X_8(TAI)	$A_i = \frac{\sum_{j=1}^{n}(H_{ij} \times w_j)}{\sum_{j=1}^{n} w_j}; w_j = \sqrt{P_j \times G_j}$ where A_i is the weighted average travel time for node i, n is the number of nodes (14 prefecture-level cities in Liaoning in this study), H_{ij} is the shortest travel time from node i to node j, w_j is the weight of node j, P_j is the total population of node j, and G_j is the GDP of node j. In this study, the traffic accessibility index is the reciprocal of the weighted average travel time.	Population and GDP data are sourced from the "2019 Liaoning Statistical Yearbook." https://tjj.ln.gov.cn/ City and road vector data are sourced from the National Basic Geographic Information Center's 1:1,000,000 data. http://www.ngcc.cn/

spatial non-stationarity of influencing factors. (Fotheringham et al., 2002) The GWR model is expressed as follows:

$$y_i = \beta_0(\mu_i, v_i) + \sum_{k=1}^{n} \beta_k(\mu_i, v_i)x_{ik} + \varepsilon_i \qquad (7)$$

where y_i is the global dependent variable; $\beta_0(\mu_i, v_i)$ is the estimated value of the constant term, (μ_i, v_i) are the geographical coordinates of the ith sample, n is the number of independent variables, $\beta_k(\mu_i, v_i)$ is the estimated coefficient of the kth independent variable within the ith sample space, x_{ik} is the observed value of the kth independent variable within the ith sample space, and ε_i is the error term.

Results

Spatial distribution patterns of traditional Villages in Liaoning Province

Spatial distribution type. The spatial distribution of traditional villages in Liaoning follows a clustered pattern. Using the "Average Nearest Neighbor" module in the "Spatial Statistics Tools" of ArcGIS10.8, the average observed distance, $\bar{r}_1$, for 78 traditional villages in Liaoning was calculated to be 18.307 km, with an expected average distance, r_E, of 23.994 km. The nearest neighbor index, R, was 0.763 $(R < 1)$, while the z-score was −4.004, passing the 1% significance test $(P = 0.000)$. Accordingly, the spatial distribution type of traditional villages in Liaoning is clustered to a significant degree.

Spatial distribution balance
Measurement of the spatial distribution balance: In Liaoning Province, the number of traditional villages remains consistent across certain geographical regional scale as well as at the municipal scale. In this case, the balance of their spatial distribution cannot be solely measured by the number alone. Therefore, the Gini coefficient can be utilized to objectively calculate the degree of concentration, providing a more objective

Table 5 Statistical table of traditional villages of the geographical region in Liaoning.

Georegion	Number of Traditional Villages	Traditional Village Proportion (vi)	Georegional Area (km²)	Area Proportion (ai)	Village Ratio (vi/ai)	Cumulative Traditional Village Proportion (Qi)
Eastern Liao	9	0.1154	39,746	0.26747	0.4314	0.1154
Southern Liao	5	0.0641	17,986	0.12104	0.5296	0.1795
Northern Liao	5	0.0641	17,572	0.11825	0.5421	0.2436
Central Liao	9	0.1154	22,360	0.15047	0.7668	0.3590
Western Liao	50	0.6410	50,936	0.34277	1.8701	1.0000

Table 6 Statistical table of traditional villages of city region in Liaoning.

City	Number of Traditional Villages	Traditional Village Proportion (vi)	City Area (km²)	City Area Proportion (ai)	Village Ratio (vi/ai)	Cumulative Traditional Village Proportion (Qi)
Liaoyang	0	0	4802	0.0323	0	0
Yingkou	0	0	5436	0.0366	0	0
Dandong	3	0.0385	15,336	0.1032	0.3727	0.0385
Benxi	2	0.0256	8439	0.0568	0.4515	0.0641
Fuxin	3	0.0385	10,386	0.0699	0.5503	0.1026
Tieling	4	0.0513	13,024	0.0876	0.5851	0.1538
Shenyang	4	0.0513	12,899	0.0868	0.5908	0.2051
Fushun	4	0.0513	11,305	0.0761	0.6741	0.2564
Dalian	5	0.0641	13,284	0.0894	0.7171	0.3205
Anshan	4	0.0513	9291	0.0625	0.8202	0.3718
Panjin	2	0.0256	4115	0.0277	0.9259	0.3974
Huludao	7	0.0897	10,447	0.0703	1.2765	0.4872
Jinzhou	9	0.1154	10,078	0.0678	1.7013	0.6026
Chaoyang	31	0.3974	19,757	0.1330	2.9892	1.0000
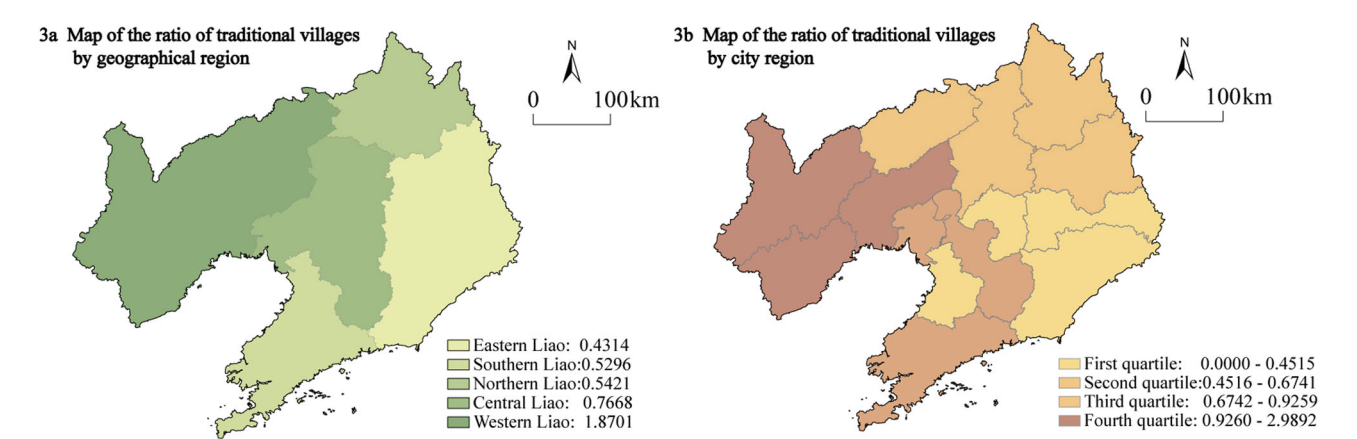
Fig. 3 Map of distribution equilibrium of traditional villages in Liaoning. The spatial distribution of traditional villages in Liaoning exhibits a clustered pattern: In terms of the geographical regional scale, the distribution is highly uneven and mainly concentrated in the western region of Liaoning. At the municipal scale, the distribution is relatively uneven and primarily located in the cities of Chaoyang, Jinzhou, Huludao, Panjin, Anshan, and Dalian.

measure of the balance of their spatial distribution. The area proportion, traditional village proportion, village ratio, and cumulative traditional village proportion were obtained based on the area proportions of the geographical regions in Liaoning (Table 5) and the areas of the 14 cities and the number of traditional villages (Table 6). Using formulas (4) and (5), this study obtained the following results. (1) On the geographical regional scale, the Gini coefficient, G, for the spatial distribution of traditional villages in Liaoning is 0.67 ($G > 0.6$), indicating a highly uneven distribution. (2) on the municipal scale, the Gini coefficient, G, for the spatial distribution of traditional villages in Liaoning is 0.58 ($0.5 \leq G < 0.6$), indicating a relatively uneven distribution.

Spatial distribution characteristics at different scales: On the geographical scale, results revealed that the spatial distribution of traditional villages in Liaoning is highly uneven and primarily concentrated in the western region of Liaoning. As Table 5 and Fig. 3a show, there is a noticeable disparity in the distribution of traditional villages at the geographical regional scale. The western region of Liaoning has the highest number of traditional villages (ratio of 1.8701), followed by the central region (ratio of 0.7668). The northern and southern regions show little difference (ratios of 0.5421 and 0.5296, respectively), while the eastern region has the fewest traditional villages (ratio of 0.4314). This distribution results in a spindle-shaped pattern characteristic, with a heavier
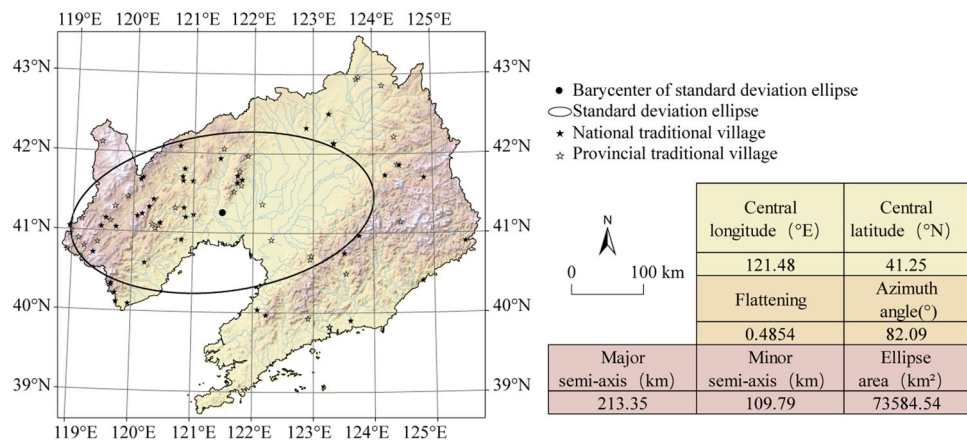
Fig. 4 Standard deviation elliptic of traditional village distribution in Liaoning province. The majority of traditional villages are distributed along the southwest–northeast axis of the standard deviation ellipse, which corresponds with the main mountain ranges of Liaoning.

cluster in the west, lighter in the east, and slight prominence in the central region.

On the municipal scale, the spatial distribution of traditional villages in Liaoning is relatively uneven and mainly distributed in the cities of Chaoyang, Jinzhou, Huludao, Panjin, Anshan, and Dalian. Figure 3b visually present the spatial distribution characteristics of traditional villages at the municipal scale, with the distribution ratios of the traditional villages in each city classified using the quantile method in ArcGIS10.8. As Table 6 and Fig. 3b show, the cities of Chaoyang, Jinzhou, and Huludao have the highest number of traditional villages, falling into the fourth quartile. This is followed by the cities of Panjin, Anshan, and Dalian, which fall into the third quartile. The cities of Fuxin, Tieling, Shenyang, and Fushun are in the second quartile. In contrast, the cities of Liaoyang, Yingkou, Dandong, and Benxi have few or no traditional villages, placing them in the first quartile.

Spatial distribution directionality. The majority of traditional villages in Liaoning are distributed along the southwest–northeast axis of the standard deviation ellipse, aligning with the main mountain ranges of the province. This study calculated the standard deviation ellipse of the distribution of traditional villages in Liaoning using the "Directional Distribution" module in the "Spatial Statistics Tools" of ArcGIS10.8. As Fig. 4 shows, the long axis of the standard deviation ellipse measures 213.35 km, extending from the western part of Chaoyang in the west to the western parts of Fushun and Benxi in the east. The short axis measures 109.79 km, reaching from the central part of Fuxin in the north to the central part of Yingkou in the south. The ellipse area is 73,584.54 km², indicating that these regions are high-density areas for traditional villages in Liaoning. The centroid of the standard deviation ellipse is located in the northeastern part of Linghai (121.48°E, 41.25°N), indicating that the distribution center of traditional villages leans toward the western part of the province, forming a pattern of more villages in the west and fewer in the east with the Liao River as the boundary. This finding is consistent with previous analyses. The flatness of the standard deviation ellipse is 0.4854, and the rotation angle is 82.09°, indicating a certain direction in the spatial distribution, with most traditional villages distributed along the southwest–northeast axis, corresponding with the direction of the main mountain ranges in Liaoning.

Spatial distribution aggregation characteristics. The spatial distribution density of traditional villages in Liaoning exhibits

characteristics of continuous clustering in the west, scattered clustering in the central and eastern parts, and clustering on the edge. Using the "Kernel Density" module in the "Spatial Analyst Tools" of ArcGIS10.8, this study performed calculations at 10-km search radii intervals from 10 km to 100 km (i.e., 10 km, 20 km, 30 km, and so on until 100 km). In doing so, this study found that kernel density results with a 50 km search radius best reflect the regional differences. Illustrated in Fig. 5, findings can be summated as followed. (1) Three high-density cores (IV density areas) of traditional village distribution were identified in Liaoning: the junction of Chaoyang, Huludao, and Jinzhou; the junction of Fuxin and Jinzhou; and the junction of Huludao and Qinhuangdao. (2) This study identified five secondary density cores (III density areas) in Liaoning: a continuous ring-shaped area around the periphery of the three high-density cores; northern Tieling near Shenyang; central Shenyang near Tieling; the junction of Fushun and Tieling; and the junction of Dalian and Dandong. (3) Comprehensive analysis revealed all three high-density cores are located in the western region, with a surrounding ring of secondary density cores, indicating a continuous clustering characteristic in the distribution of traditional villages in western Liaoning. Other secondary-density cores are scattered in the northern, eastern, and southern regions of Liaoning, evidencing a scattered clustering characteristic in the central and eastern parts of the province. The appearance of these density cores at or near the borders of various cities is indicative of an edge clustering characteristic in the spatial distribution of traditional villages in the province.

Influence of human settlements factors on spatial distribution patterns

OLS model results. Before conducting the GWR model analysis, this study conducted regression analysis using an OLS model. As Table 7 shows, the variance inflation factors (VIF) are all less than 7.5, indicating no multicollinearity among the explanatory variables and that the model setup is reasonable. The NDVI was not statistically significant ($P = 0.206$). Therefore, seven factors were ultimately used as the influencing factors of the spatial distribution patterns of traditional villages in Liaoning: namely, TRI, CCI, HI, LCI, NLI, CDI, and TAI. This study subsequently used the GWR model to explore the spatial variability of their effects.

GWR model results. As Table 8 shows, the R^2 value and adjusted R^2 of the GWR model are significantly higher compared to the OLS model, and the AICc value of the GWR model is more than 3 points lower than that of the OLS model, indicating a better fit
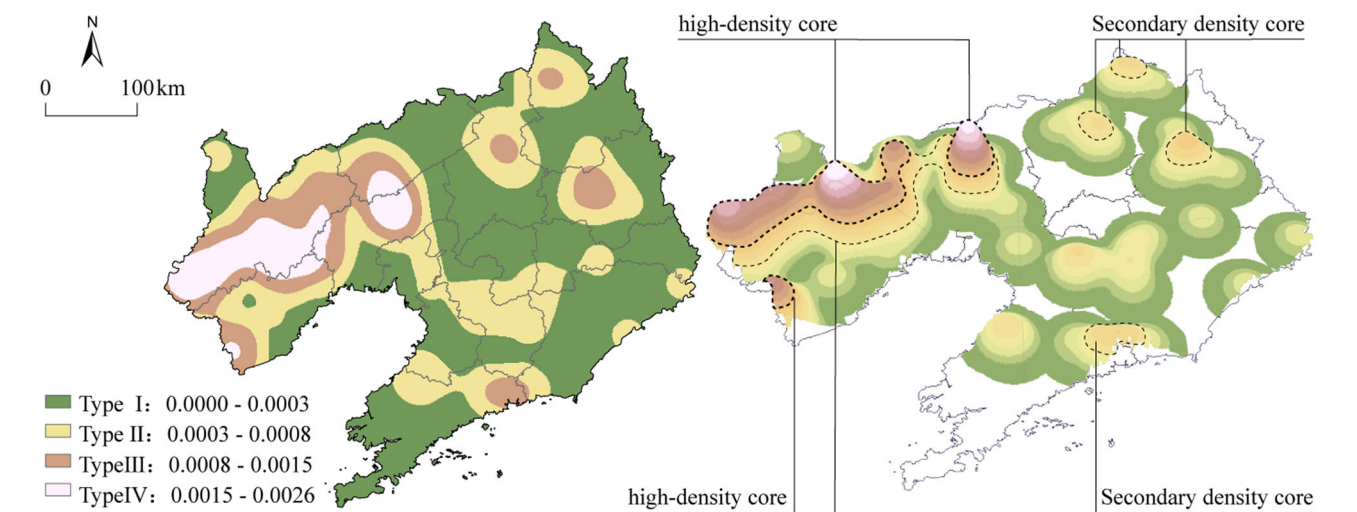
Fig. 5 Kernel density of traditional villages in Liaoning province. The distribution density features a western continuous clustering, central and eastern scattered clustering, and edge clustering pattern.

Table 7 Main parameters of OLS model estimation.

Variable	coefficient	P Value	VIF Value
X_1(TRI)	0.5269	0.000[a]	2.8669
X_2(CCI)	0.3564	0.000[a]	1.2271
X_3(HI)	−0.3072	0.000[a]	2.1758
X_4(NDVI)	0.0551	0.206	5.1810
X_5(LCI)	0.1085	0.000[a]	3.3634
X_6(NLI)	−0.0507	0.006[a]	1.3929
X_7(CDI)	0.3830	0.000[a]	1.4564
X_8(TAI)	−0.2792	0.000[a]	1.2271

[a]indicates significance at the 0.05 level ($P < 0.05$).

Table 8 Comparison of the main parameters of the OLS model and GWR model.

Parameter	OLS Model	GWR Model
R^2	0.4497	0.6989
Adjusted R^2	0.4471	0.6864
AIC_C	3754.10	2834.27

of the GWR model. The standardized residual values range from −3.34 to 4.52, with 97% of the values falling between −2.5 and 2.5, indicating that the standardized residuals are randomly distributed at the 95% significance level. The condition number ranges from 3.2544 to 29.9883, within the 0 to 30 range, demonstrating that the model passes the local multicollinearity diagnosis. These results suggest that the overall model performance is quite good. In addition to model estimation, this study conducted a statistical analysis of the ratios of the positive and negative regression coefficients for each influencing factor (Fig. 6a) and used ArcGIS10.8 to visualize the spatial variability of the regression coefficients (Fig. 6b), illustrating the differences in how various human settlements indices affect the spatial distribution of traditional villages.

Result analysis. The influence of various human settlements factors on the spatial distribution patterns of traditional villages

significantly varies in nature and intensity (Table 7). (1) the influence intensity of factors can be gauged on the basis of the average absolute values of the regression coefficients. Analysis revealed the following ranking in ascending order from highest to lowest influence intensity: TRI, CDI, CCI, HI, TAI, LCI, and NLI. (2) in terms of the sign of the regression coefficients, HI, NLI, and TAI negatively impacted the spatial distribution patterns of traditional villages, while all other factors had a positive impact.

Natural factors: Natural factors of human settlements had a primarily positive impact and exhibited the highest influence intensity, making them the dominant factors in forming the spatial distribution patterns of traditional villages. Among natural factors, TRI, CCI, and HI had the most pronounced impact.

(1) The TRI had a predominantly positive influence on the spatial distribution patterns of traditional villages (Fig. 6a), with the impact coefficient showing a spatial differentiation pattern of positive influence in the west gradually transitioning to negative influence in the southeast (Fig. 6b-1). The regions with the high positive values are located in the western parts of the cities of Chaoyang, Huludao, Jinzhou, and Fuxin. These areas are located in the mountainous and hilly regions of western Liaoning, including the mountain ranges of Mt. Nulu'erhu, Mt. Daqing, Songling, and Mt. Yiwulü, with elevations around 1000 meters. Such significant terrain ruggedness tends to create relatively enclosed environments, forming distinctive rural settlements that have been well-preserved over history due to minimal external disturbances.

(2) The CCI also had a largely positive impact on the spatial distribution patterns of traditional villages (Fig. 6a), with the impact coefficient showing a spatial differentiation pattern of positive influence in the west gradually transitioning to negative influence in the south (Fig. 6b-2). Climate comfort refers to climatic conditions that allow normal physiological activities without the need for measures against cold or heat, which is especially important for rural areas with relatively poor economic and municipal infrastructure. Regions with high positive values are located in Chaoyang, Huludao, and Jinzhou, with climate comfort decreasing from the Liaodong Peninsula and the southwest coast to the northeast of Liaoning. This finding indicates that climate comfort is one
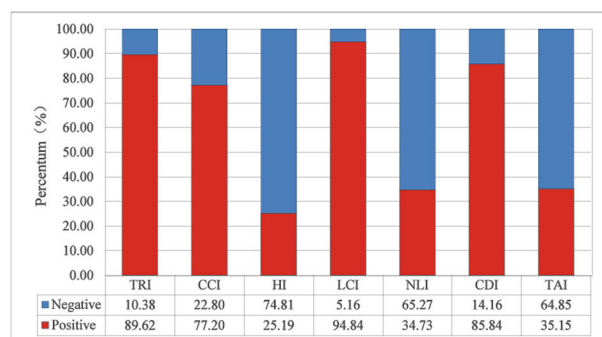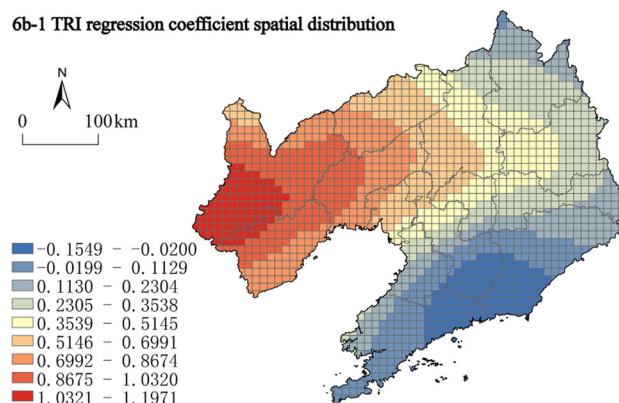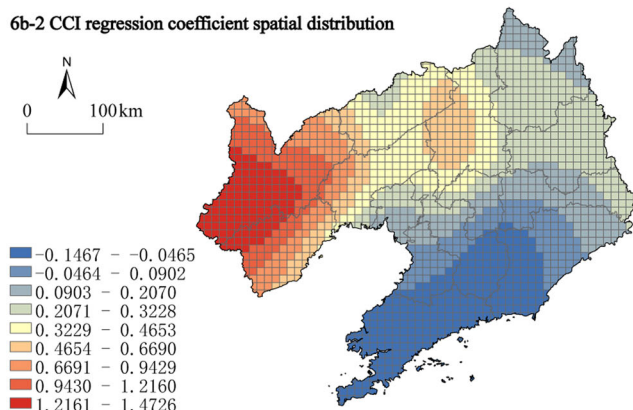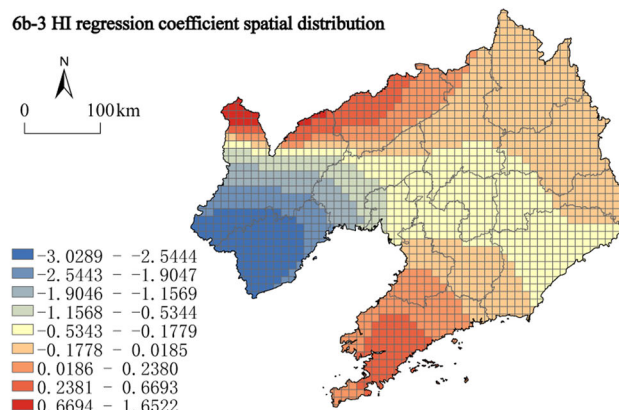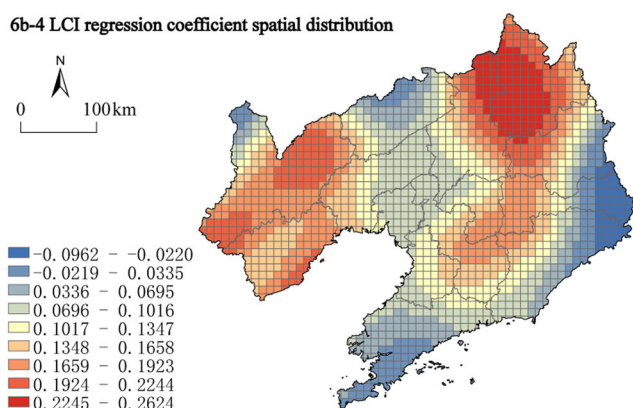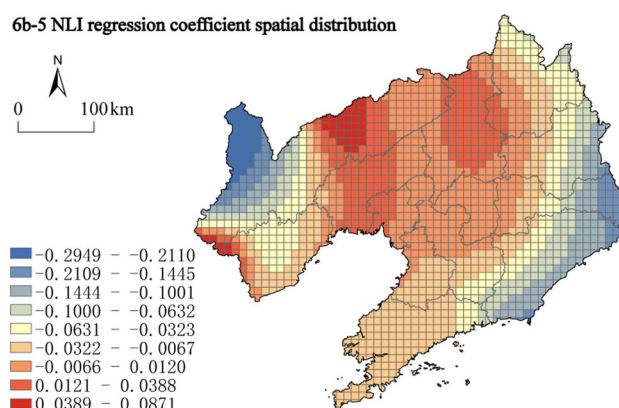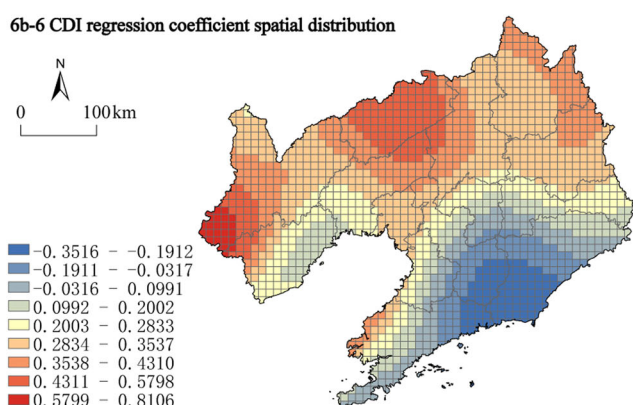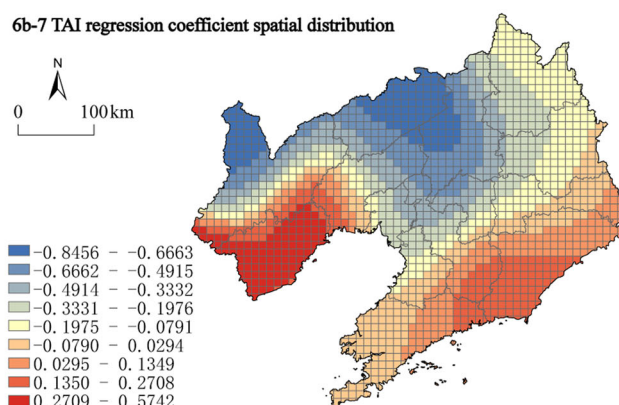
Fig. 6 Regression coefficient of influencing factors of the spatial distribution of traditional villages in Liaoning. The spatial distribution patterns of traditional villages in Liaoning are influenced by various human settlements factors, with spatial variation in the nature and intensity of the effects of these factors. The natural factors of human settlements are the dominant factors in the spatial distribution patterns of traditional villages, while the humanistic factors of human settlements have a dual impact on these patterns.

of the dominant factors in the site selection of traditional villages in Liaoning.

(3) The HI was found to have a mainly negative impact on the spatial distribution patterns of traditional villages (Fig. 6a), with the impact coefficient showing a spatial differentiation pattern of positive influence in the north and south, gradually transitioning to a negative influence in the center (Fig. 6b-3). The cities with the highest number of traditional villages—such as Chaoyang, Huludao, and Jinzhou—are located in areas with the poorest hydrological conditions in the province. At first glance, the hydrological index seems to have a negative impact, contradicting the general knowledge of site selection for traditional villages. However, the hydrological conditions in these areas were better in ancient times than in modern times. Additionally, despite the low precipitation in more recent history, traditional villages are mainly distributed along the Daling and Xiaoling rivers and their tributaries, suggesting that hydrological conditions are also a dominant factor in forming the spatial distribution patterns of traditional villages.

Humanistic factors: Humanistic factors of human settlements have a twofold impact on shaping the spatial distribution patterns of traditional villages: where the CDI and LCI have a primarily positive impact, the NLI and TAI have a negative and limiting influence.

(1) As noted, the CDI and LCI have a primarily a positive impact. Although exhibiting lower influence intensity compared to natural factors, they are still important factors in forming the spatial distribution patterns of traditional villages. More specifically, the CDI positively impacts the spatial distribution patterns of traditional villages (Fig. 6a), with the impact coefficient showing a spatial differentiation pattern of positive influence in the northwest gradually transitioning to negative influence in the southeast (Fig. 6b-6). Regions with high positive values are located in Chaoyang, Huludao, Fuxin, Jinzhou, and Shenyang. These areas have a long history and rich cultural resources. For instance, the Niuheliang Hongshan Culture site discovered in Chaoyang evidences the existence of a primitive civilized society and rudimentary state about 5000 years ago, forming part of the origins of Chinese civilization. Huludao and Jinzhou are located in the "Western Liaoning Corridor," a bridge for cultural exchanges between central regions and northeastern ethnic minorities. As one of the birthplaces of the Qing Dynasty, Shenyang is known as "the birthplace of one dynasty and the capital of two emperors." As such, these regions have nourished numerous charming traditional villages. The LCI also has a primarily positive impact on the spatial distribution patterns of traditional villages (Fig. 6a), with the impact coefficient showing a spatial differentiation pattern of positive influence in the northwest that gradually transitions to a negative influence in the southeast (Fig. 6b-4). Regions with high positive values are located in Chaoyang and Huludao, as well as the border areas of Shenyang, Tieling, and Fushun cities. These areas lie in the farming–grazing transitional zone, where intense agricultural and pastoral activities have significantly altered the land cover. Moreover, the engagement of significant proportions of the population in agriculture and animal husbandry has created numerous distinctive rural settlements, facilitating the formation of traditional villages.

(2) Although their influence intensity is subtle, the NLI and TAI have a negative impact and act as limiting factors in

forming the spatial distribution patterns of traditional villages. More specifically, the NLI negatively impacts the spatial distribution patterns of traditional villages (Fig. 6a), with the impact coefficient showing a spatial differentiation pattern of positive influence in the center, which then transitions to a negative influence on both the east and west sides (Fig. 6b-5). Meanwhile, the TAI has a primarily negative impact on the spatial distribution patterns of traditional villages (Fig. 6a), with the impact coefficient showing a spatial differentiation pattern of positive influence in the southeast coastal area that gradually transitions into a negative influence in the northwest inland region (Fig. 6b-7). Both NLI and TAI reflect the level of socioeconomic development and how well materials, information, and people flow. Their primarily negative impact indicates that, for most regions, relatively under-developed economies and infrastructure preserve traditional villages from the effects of urbanization and modernization, facilitating their ability to remain intact. Otherwise, these factors may lead to the assimilation of traditional villages, hindering their preservation.

Conclusion and discussion

The protection and utilization of traditional villages has been transformed from individual village to regional groups, and scientifically analyzing the spatial distribution pattern of traditional villages based on zoning, exploring their influencing factors, and formulating targeted protection strategies has become an urgent scientific problem to be solved. In this study, we selected Liaoning Province, a typical example of traditional village protection pressures in China, as a case study area (Fig. 7). We employed the nearest neighbor index, the Gini coefficient, the standard deviation ellipse, and the kernel density estimation method to delineate the spatial distribution pattern of traditional villages and identify the traditional village agglomeration areas. Furthermore, we utilized the OLS model and the GWR model to detect spatial heterogeneity of the influence of natural and humanistic factors on the spatial distribution pattern, thereby proposing targeted conservation strategies. Overall, this study offers scientific and theoretical support for the development of rural geography and geography of human settlements, the conservation and utilization of traditional villages in Liaoning Province, and serves as a reference for exploring conservation modes of traditional villages on a macro scale in other regions of China and even globally.

Conclusions. The main findings of this study can be summarized as follows.

(1) The spatial distribution of traditional villages in Liaoning is highly uneven and exhibits significant clustering characteristics. More specifically, the spatial distribution of traditional villages in Liaoning is clustered. At the geographical regional scale, the distribution is highly uneven and mainly concentrated in the western region of Liaoning. At the municipal scale, the distribution is relatively uneven and primarily located in the cities of Chaoyang, Jinzhou, Huludao, Panjin, Anshan, and Dalian. The majority of traditional villages are distributed along the southwest–northeast axis of the standard deviation ellipse, which is consistent with the direction of the main mountain ranges of Liaoning. Moreover, the distribution density exhibits characteristics of continuous clustering in the west, scattered clustering in the central and eastern parts, and clustering on the edge.

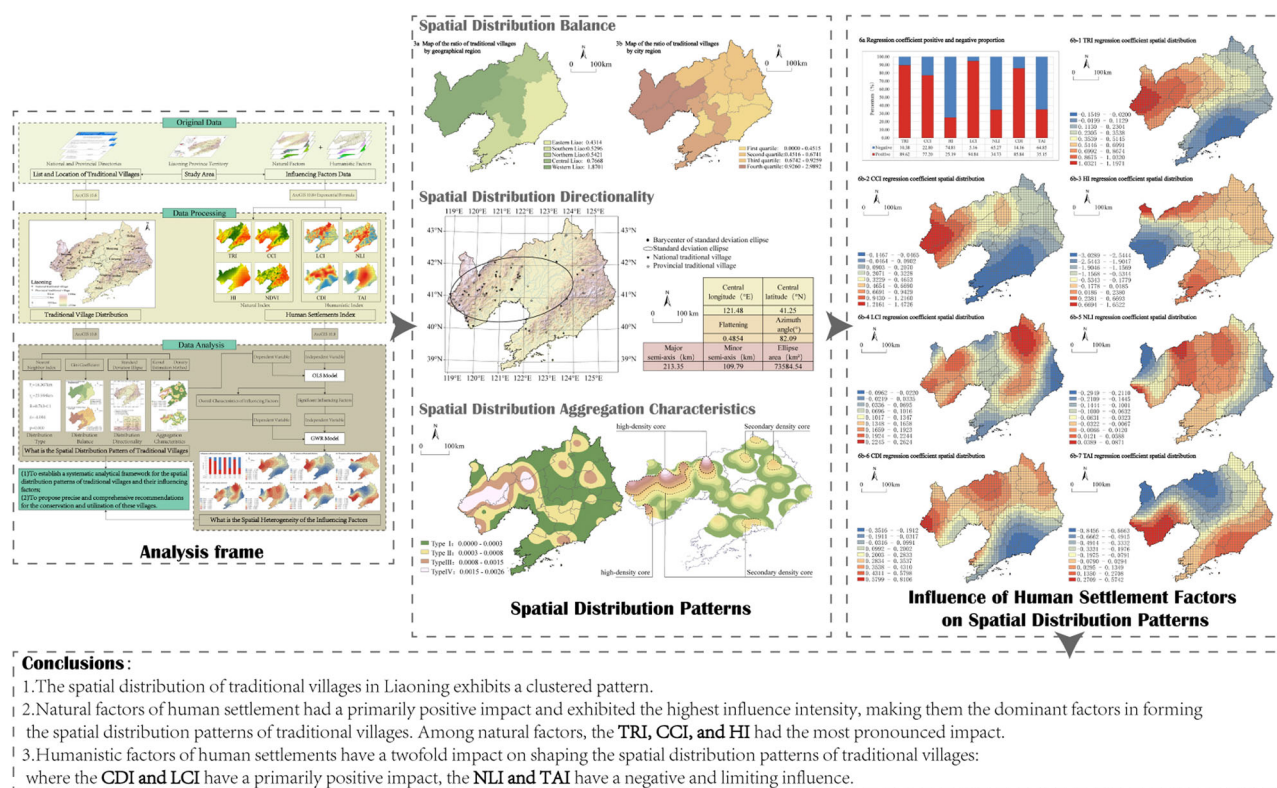(2) The spatial distribution patterns of traditional villages in Liaoning are influenced by various human settlements

Fig. 7 Graphical abstract. The graphics of this study mainly include three parts: analysis frame, spatial distribution patterns and influence of human settlement factors on spatial distribution patterns.

factors, with spatial variations in the nature and intensity of these influence factors. More specifically, natural factors of human settlements have a primarily positive impact and exhibit the highest influence intensity, making them the dominant factors in the formation of the spatial distribution patterns of traditional villages. Among these factors, the TRI, CCI, and HI are the most notable. Meanwhile, humanistic factors of human settlements exhibit a dual impact on the spatial distribution patterns of traditional villages. In this respect, the CDI and LCI exert a positive impact. While weaker in influence compared to natural factors, the CDI and LCI play an important role in the formation of spatial distribution patterns. In contrast, the NLI and TAI have a primarily negative impact. Although weaker in influence intensity, the NLI and TAI are restricting factors in the formation of the spatial distribution patterns of traditional villages.

Policy implications. Based on the foregoing conclusions, this study recommends the following.

(1) Establishment of hierarchical protected areas. The prominent spatial clustering characteristics of traditional villages in Liaoning Province, characterized by clear distribution directions and centers of gravity, indicate the need to establish hierarchical protected areas, as this approach facilitates the formulation of conservation policies and the rational allocation of funds (Ma et al., 2024). According to the overall pattern of traditional villages in Liaoning Province, namely, "Western contiguously clustering, central and eastern scattered clustering," this study suggests the establishment of three levels of protected areas: (1)

"Western first-level protection zone" composed of Chaoyang, Huludao, and Jinzhou; (2) the "Southern secondary protection zone" comprising Panjin, Anshan, Yingkou, and Dalian; and (3) the "northern, central and eastern general protection zone" comprising Fuxin, Tieling, Shenyang, Fushun, Liaoyang, Benxi, and Dandong.

(2) Advocate regional coordinated protection of traditional village culture. The original intention of traditional village protection is not only to protect the individuals belonging to the villages included in the list but, more importantly, to protect the cultural inheritance represented by these villages. Traditional villages in Liaoning Province have a typical "edge clustering pattern," indicating that cross-regional cultural exchanges are the basis for forming common memories of people within a certain range, which requires the government to break through the limitations of individual villages and focus on a broader scope during the implementation of protection. Emphasis should be placed on the coordination of various regions within the village cultural radiation circle (Bi et al., 2024).

(3) Shape the rural living environment of "retaining people" and promote the sustainable development of traditional villages. In western Liaoning Province, where the number of traditional villages is the largest, the quality of certain aspects of human settlements, such as hydrology, vegetation, and economy, is poor, which leads to a considerable loss of population and an environment that is not conducive to its sustainable development. For these ecologically weak and developing areas, policies and capital investment should be appropriately increased. New green and low-carbon technologies and methods should be adopted to improve the quality of their ecological environment and the level of social and economic development so as

to strengthen the resilience to disasters and risks of these villages (Fang et al., 2022; Sun et al., 2023; Li et al., 2019). In the economically developed areas represented by Shenyang and Dalian, the quality of human settlements is generally high. For these areas, the policy of protection first and development second can be adopted, on the premise of not destroying ecological environments, such as forests, and cultural landscapes, such as architecture (Chen and Nakama, 2010; Kweon and Youn, 2021; Soler-Estrela, 2018; Bura and Ando, 2023). It also makes full use of market-oriented mechanisms to actively promote the development of rural tourism, educational tourism, cultural tourism, and other tourism industries (Gao and Wu, 2017; Ruhimat et al., 2018; Mbaiwa and Sakuze, 2009; Dewia, 2014).

(4) Conscientiously implement the "Selection Method of Traditional Villages in Liaoning Province" and strengthen the survey of traditional village resources. Compared with other provinces in China, the number of traditional villages in Liaoning Province is relatively small, which does not conform to the fact that it is "one of the origins of Chinese civilization." Therefore, the government should strengthen the excavation, identification, and protection of rural culture in the primary and secondary protection areas in accordance with the law and regulations and include qualified villages in the protection list. Meanwhile, relevant studies believe that experts and local communities usually have different understandings of the concept of heritage, which will lead to differences in the designation of heritage. In view of this, the opinions of officials and villagers should be fully considered in the identification process of traditional villages so as to combine democracy with the rule of law (Katapidi, 2021).

Discussion. Based on the spatial distribution patterns of traditional villages in Liaoning, this study analyzed the influence of human settlements factors on these patterns from the perspective of regional human settlements. Compared with previous studies, this study is based on interdisciplinary thinking, more systematic in the selection of influencing factors, more multi-source in the acquisition of original data, more comprehensive in the disclosure of the formation of spatial distribution patterns, and more targeted in the formulation of protection and utilization policies; further, it has achieved the expected results. However, several issues deserve further exploration.

(1) There is a relatively small number of traditional villages in Liaoning, with even fewer villages categorized according to historical period, limiting the analysis to static spatial distribution patterns. As the recognition of traditional villages progresses, future studies should include dynamic evolution analysis of spatial distribution patterns to enhance the research outcomes.

(2) Human settlements encompass global, regional, urban, community, and building levels. This study only analyzed the impact of human settlements factors on the spatial distribution patterns of traditional villages from a provincially macro perspective, which guides macro-level policies for traditional village conservation and utilization. Future research should incorporate the micro-level analysis of specific village site selection and internal spatial layout. Exploring the influence of elements from the natural, humanistic, social, supportive, and residential systems will reveal the construction wisdom and scientific value of ancient rural human settlements, eliciting valuable insights for planning and constructing beautiful villages for living and working in contemporary China.

Data availability

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Acknowledgements

Author contributions

GT: wrote the main manuscript text, conducted the experiment, analyzed the data. ST and XL: contributed to all aspects of this work. HL and YS: Writing - Review & Editing, Supervision.

Competing interests

The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

Informed consent was obtained from all individual participants involved in the study.

Additional information

Correspondence and requests for materials should be addressed to Shenzhen Tian.

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[1]School of Geographical Sciences, Liaoning Normal University, Dalian, Liaoning, China. [2]Centre for Human Settlements, Liaoning Normal University, Dalian, Liaoning, China. [3]Research Base of Urban Agglomeration in Central South Liaoning of China Urban Agglomeration Research Base Alliance, Liaoning Normal University, Dalian, China. [4]Research Base for Synergistic Development of Human Settlements and Talents of Liaoning Province, Dalian, China. [5]University Collaborative Innovation Center of Marine Economy High Quality Development of Liaoning Province, Dalian, China. ✉email: tsz999@lnnu.edu.cn