



OPEN Spatial and temporal evolution patterns and driving mechanisms of rural settlements: a case study of Xunwu County, Jiangxi Province, China

Zexu Chen¹✉ & Huachun Dong²

Urbanization and industrialization have driven rapid socio-economic development, leading to a significant population shift from rural areas to cities. This demographic transition has resulted in substantial changes in rural settlements, presenting considerable challenges for rural revitalization. Given the spatial differentiation, it is crucial to analyze the spatiotemporal evolution patterns and driving mechanisms of rural settlements under various development scenarios and at multiple scales within a county. Such analysis is essential for rational planning and sustainable development. This study analyzes the spatial and temporal evolution patterns and driving mechanisms of rural settlements in Xunwu County, Jiangxi Province, China, using land use dynamics, hot and cold spot analysis, and center of gravity migration models. The Multiscale Geographically Weighted Regression Model (MGWR) is employed to explore their transformation driving mechanisms. The results show that during 2010–2020 in the study area, the total change rate of rural settlements was 39.82%, with a dynamic degree of 2.87%. The average centroid of the settlements is located in Wenfeng Township, gradually migrating southeastward by 3.7 km. Cold spots are shrinking northward, while hotspots are gathering in Chengjiang Town. Socio-economic conditions dominate the evolution of rural clusters in this region, showing obvious spatial heterogeneity. This is followed by locational conditions that are weakening in influence, while the impact of natural geographical conditions exists in the northeast region. The research findings offer a scientifically rigorous and well-founded analysis of the evolution and driving mechanisms of rural settlements. This analysis provides a solid theoretical basis for policy planning in urban-rural integrated development and supports the sustainable growth of rural communities.

Keywords Rural settlements, Spatiotemporal evolution, Driving mechanisms, Multi-scale geographically weighted regression, Centroid migration

Under the background of industrialization and urbanization, China's socio-economic development has rapidly progressed¹. While promoting urban-rural population movement and socio-economic interaction, the phenomenon of rural population outflow and irregular rural settlements is becoming increasingly severe². Rural settlements are small towns and villages with agricultural activities as the main focus of homesteads or farmers' settlements, whose functions are to promote the development of the primary industry, stabilize the allocation of social resources, the civilizational coupling of urban and rural societies, and regulate the rational distribution of factors of production. The uncontrolled expansion of rural settlements is often accompanied by the rough utilization of land, which may bring about a series of negative impacts, not only affecting the sustainable development of the settlements, but also putting pressure on the economic, social and ecological environment of the entire rural area. This pattern of expansion may reduce the amount of land available for agriculture, affecting food security and sustainable agricultural development, and may damage the natural environment and encroach on ecologically sensitive areas, such as wetlands and forests, resulting in the decline of biodiversity and the degradation of ecological functions³. Currently, the development of rural areas in China is relatively weak⁴.

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The government attaches great importance to rural development issues. Against the backdrop of “agriculture, rural areas, and farmers” (the “three rural” issues) and rural revitalization, promoting the socio-economic development of rural areas is a key step and has a significant impact on advancing urban-rural economic development⁵. Therefore, exploring the spatiotemporal evolution patterns and driving mechanisms of rural settlements, and then promoting the rational layout of rural settlements to achieve reasonable land resource allocation, is urgently needed to address issues such as imbalanced access to arable land, spatial reorganization of homesteads, scattered and disordered layout of construction land, and increasing environmental pressure⁶.

Rural settlements are important research objects in socio-economic development, bearing the core relationship between agricultural production activities and rural population⁷. They are focal issues in geographical studies and have received widespread attention in academia. Current scholars' research around rural settlements mainly focuses on the spatial agglomeration characteristics of rural settlements in impoverished mountainous areas⁸, ecological aesthetics of rural settlements⁹, spatial distribution patterns of settlements¹⁰, related impacts on land use¹¹, obstructive effects of rural settlements on urban expansion¹², and driving factors of spatial distribution differences¹³. In terms of the spatiotemporal evolution pattern of rural settlements, scholars mainly use the scale and density of settlements as the basis¹⁴, adopting spatial measurement indices¹⁵, gradient sample belts¹⁶, statistical and spatial analysis methods to explore the spatial agglomeration characteristics¹⁷, river distribution characteristics¹⁸, road distribution characteristics of settlements¹⁹, etc. This to some extent reveals the spatial distribution evolution of rural settlements, but it is difficult to reflect the spatial scale differences of settlements at the micro level and ignores the impact of human social factors on them²⁰. When discussing the driving mechanisms affecting settlement evolution, current research mainly selects indicators from natural geography²¹, resource endowment²², location conditions²³, socio-economic aspects²⁴, etc., using geographic detectors²⁵, spatial regression models²⁶, geographically weighted regression methods²⁷, etc., to construct evaluation frameworks to identify and reveal the influence of driving factors, achieving some important results²⁸. However, few studies have explored the interactions between various driving factors at different scales and lacked discussion on the coupling mechanism in the driving mechanism, unable to optimize the spatial pattern of rural settlements from the perspectives of natural ecology and socio-economy²⁹. Simultaneously, several scholars have investigated the fragmentation of open space within the urbanization process and its resultant social inequality and developmental disparities, particularly in the context of rapidly developing high-density cities. By means of geographical exploration model and principal component analysis, they reveal the spatial heterogeneity and driving mechanism under different regions, development stages and urban growth patterns, providing important implications for urban planning and sustainable development^{30–32}. Current research on rural settlements mainly focuses on the spatial and temporal distribution at macro or micro scales, or on the analysis of pattern transformation factors in a typical region³³. However, as a large number of people move to the cities, the evolution of rural settlements has become more and more complex. The analysis of the spatial and temporal evolution of settlements and their driving mechanisms from the perspective of human-land relations in different contexts is a key task in rural revitalization and territorial spatial planning³⁴.

This study, grounded in current rural development trends and adopting a county-level spatial perspective, utilizes the calculation of land use dynamics to determine the migration rates and scales of rural settlements. This approach enables the monitoring of settlement changes across horizontal space. The centroid migration model and hot-spot/cold-spot analysis are employed to simulate the spatiotemporal evolution of these settlements. Through this methodology, we explore the migration paths, spatial layouts, and morphological characteristic differences of the rural settlement centroids over the study period. We used the MGWR model³⁵ to conduct characteristic multicollinearity tests and independent variable correlation analyses on the drivers, and then obtained the more influential drivers, so as to reveal a more scientific and comprehensive driving mechanism in the evolution of rural settlements. This aims to provide a reference for optimizing the spatial layout of rural settlements, holds significant importance for the integrated development of urban and rural areas, promoting the implementation of rural revitalization strategies, and offers a theoretical basis for national spatial planning and socio-economic development policy formulation.

Study area and data sources

Study area

Xunwu County is located in Ganzhou City, Jiangxi Province in southern China, at the junction of Jiangxi, Fujian and Guangdong Provinces (Fig. 1). The terrain presents a spoon-shaped distribution, with high elevations around and low in the middle, forming a stepwise pattern. The geographical coordinates of Xunwu County range from 24°30' to 25°12'N and 115°21' to 115°54'E. It is a typical southern hilly mountainous city, with mountainous areas covering 1748 km², accounting for 75.62% of the total land area. Rural settlements cover an area of 26.93 km², encompassing 15 townships. The county belongs to the subtropical monsoon climate with an average annual temperature of 18.9 °C and an average annual precipitation of 1650.3 mm.

Against the backdrop of rural revitalization, Xunwu County has made significant socio-economic progress. Efforts have been made to build Xunwu into a red culture heritage innovation zone, a concentrated fruit industry resource area in southern Jiangxi, and an ecological demonstration zone in the Dongjiang River Basin. However, due to insufficient government support for rural revitalization industries, the siphon effect of surrounding developed cities, and the gradual decrease in rural population in Xunwu County, the spatiotemporal distribution of rural settlements has been severely affected. Xunwu County has a rich historical and cultural heritage, and many traditional villages have been preserved, which have experienced many social changes and are of high value for the study of the historical evolution of rural settlements. Therefore, the morphological evolution of rural settlements in the study area is an important research direction in the context of geographic conditions, social culture, policy conditions and economic development. Therefore, exploring and analyzing the evolution

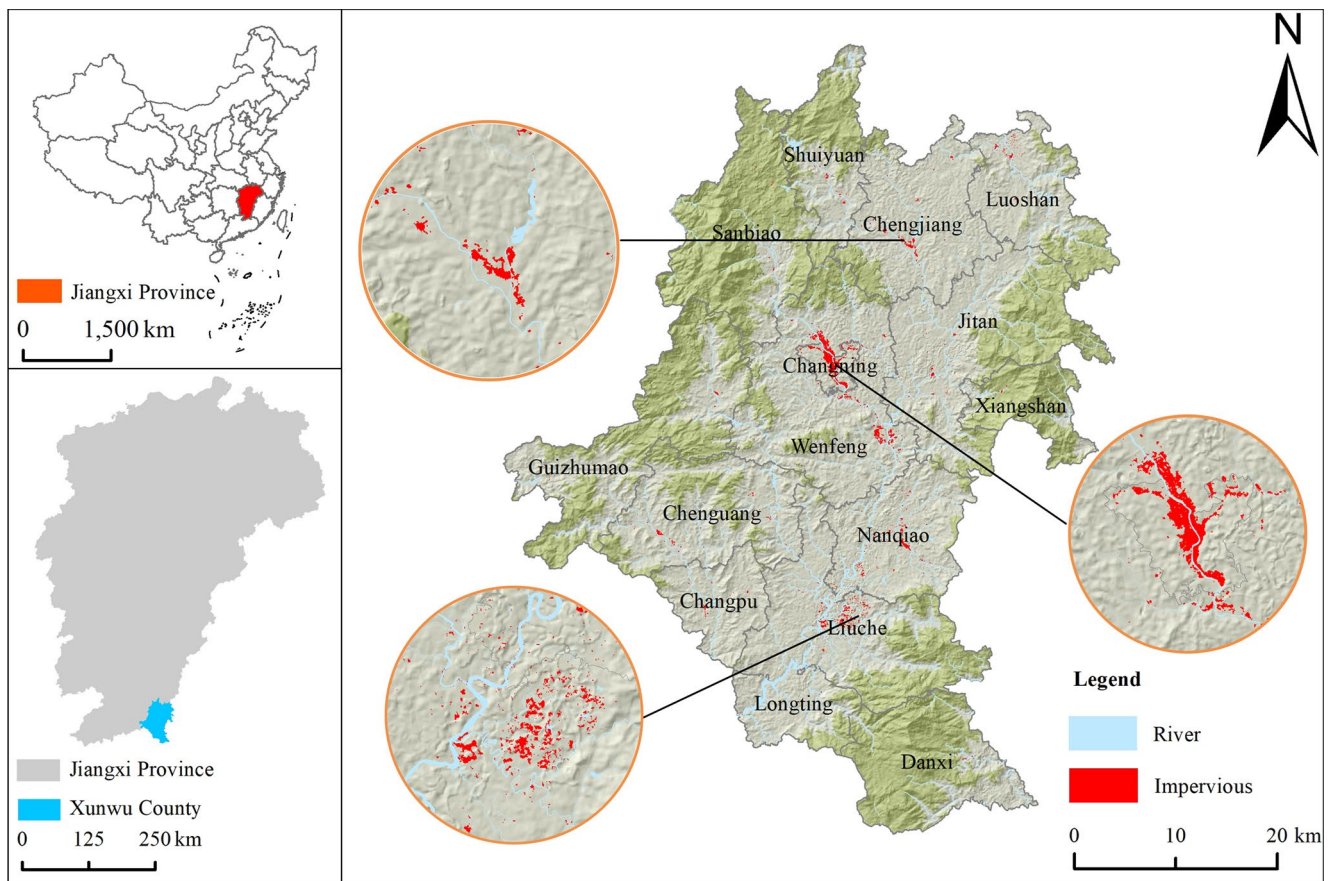


Figure 1. Location map of the study area. Figure 1 was generated by the manuscript author using ArcGIS 10.2 software. Software version number is 10.2, the link to <https://desktop.arcgis.com/>.

and driving mechanisms of rural settlements in Xunwu County from multiple perspectives is urgently needed to promote rural industrial revitalization and sustainable economic development.

Data sources and processing

This study uses the China Multi-Period Land Use Remote Sensing Monitoring Dataset (CNLUCC). This dataset uses LandsatTM/ETM remote sensing images as the main data source, and spatial cropping is performed through the GIS platform to obtain the 2010 land use data and 2020 land use data of Xunwu County, with a resolution of 30 m×30 m. The data are used to monitor the land use of the county in 2010 and 2020, respectively. CNLUCC adopts a two-tier classification system, with the first tier divided into six categories, namely, arable land, forest land, grassland, waters, construction land and non-utilised land, mainly based on land resources and their utilisation attributes, and the second tier is divided into 23 types, mainly based on the natural attributes of land resources, which include the land use types of rural settlements. Based on the 2010 and 2020 land use data in the GIS platform, the vector map patches of settlements were extracted as the rural settlement data of the current period. Elevation (DEM) data was sourced from the Geospatial Data Cloud (<http://www.gscloud.cn/>), using the ASTER GDEM (V1) product with a spatial resolution of 30×30 m. GIS technology was employed to extract slope, aspect, and terrain relief data. Raster data such as population, GDP, and soil were sourced from the Resource and Environmental Science and Data Center (<https://www.resdc.cn/>). Road and river data were obtained from the National Geographic Information Center's road database (<http://www.ngcc.cn>). Socio-economic statistical data, such as GDP, rural population numbers, and grain crop yields, were all derived from the annual statistical yearbooks of Xunwu County over the years.

Research ideas and methods

In our study of the spatiotemporal evolution of rural settlements, we focus on changes in their location and scale over time, as well as the underlying driving factors. By employing landscape ecology indicators and spatial analysis methods, we delve into the distribution characteristics and identify hotspots of change within these settlements. Our research takes a comprehensive approach, considering multiple driving forces such as natural conditions, economic policies, and socio-cultural elements. From a sustainability perspective, we assess environmental impacts, predict future trends, and provide a scientific foundation along with strategic recommendations for rural revitalization and land management. The specific research framework and methodologies are illustrated in Fig. 2.

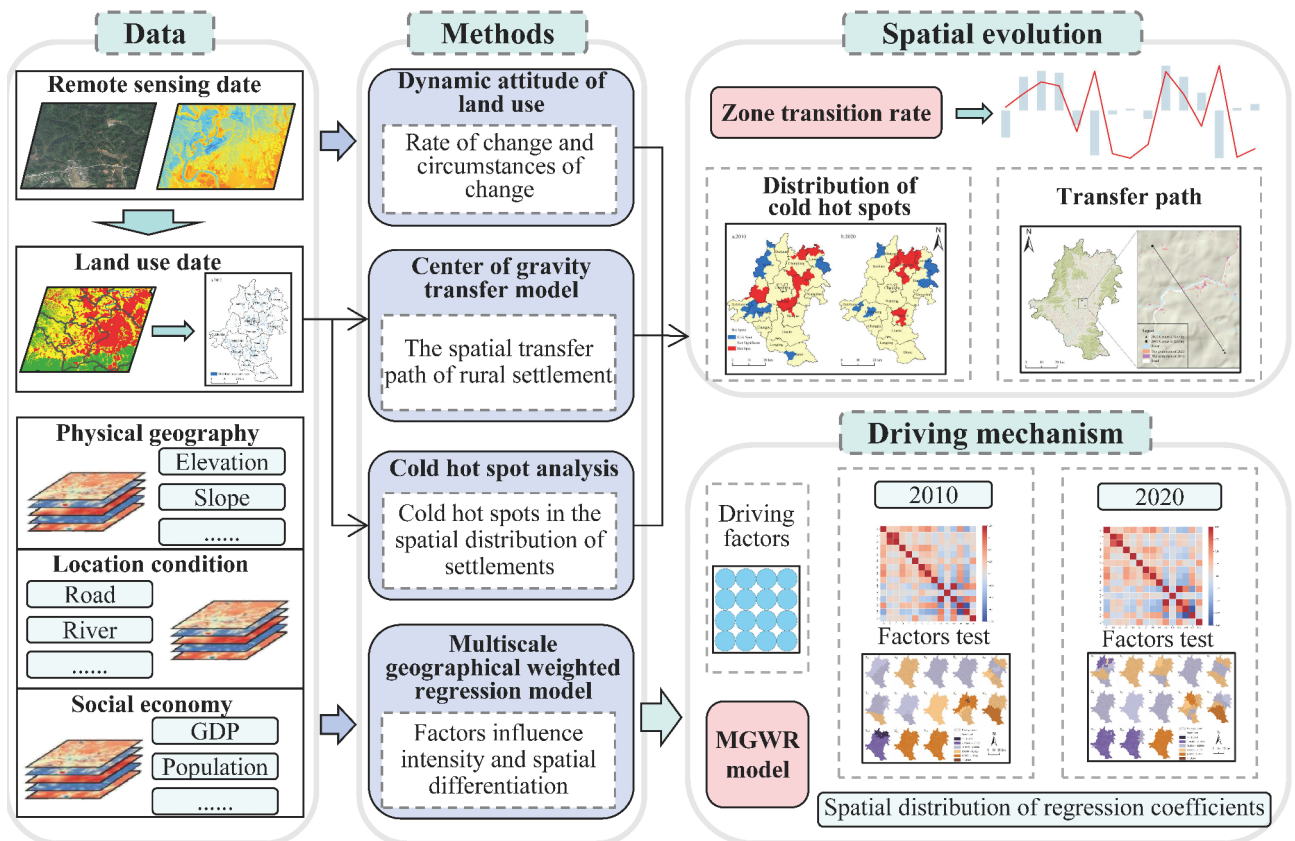


Figure 2. Technical process circuit diagram.

Dynamic degree of land use

The degree of land use dynamics can reflect the speed and changes of various types of land in a specific period within the study area. It has high scientific validity in revealing the rate and extent of land type transformations, and can effectively analyze the quantity, structure, and form of rural settlements from a macro perspective at different times³⁶. The degree of land use dynamics is divided into single land use dynamic degree and comprehensive land use dynamic degree. This study uses land use data as the basis, extracts rural residential plot data as rural settlement plots, and uses the single land use dynamic degree to quantitatively analyze the changes in the number and area of rural settlements in the study area, as well as the evolution of settlement structures. The calculation formula is³⁷:

$$K = \frac{S_m - S_n}{S_n} \times \frac{1}{T} \times 100\% \quad (1)$$

in Eq. (1), K represents the dynamic utilization degree of rural settlements during a characteristic period in the study area; S_n and S_m are the areas of rural settlements at the beginning and end of the research period, respectively; T is the time interval between the beginning and end of the research period. The larger the absolute value of K, the faster and more significant the rate of change in the types of land use in rural settlements.

Center of gravity transfer model

The centroid migration model can dynamically analyze spatial changes, demonstrating high flexibility and efficiency. It can also provide detailed spatiotemporal evolution paths under different scenario changes, and is widely used in resource optimization and strategy implementation³⁸. Taking the 15 township administrative areas under the jurisdiction of Xunwu County as the basic units for spatial differentiation, a centroid migration model for the spatial transformation of rural settlements in Xunwu County is constructed based on the theory of centroids. This model analyzes the spatiotemporal distribution change rules of rural settlements in the study area from 2010 to 2020. Using the spatial patches of rural residential points in 2010 as the research base period, and those in 2020 as the comparison period, the distribution centroids of rural settlement transformations during the research base period and comparison period are analyzed through the centroid migration model. The results of the spatial transfer evolution of settlements within the research period are obtained, and the spatial analysis function of GIS technology is used to identify and label the location of the transfer centroid. The calculation formula is as follows³⁹:

$$X = \sum_{i=1}^n P_i X_i / \sum_{i=1}^n P_i \quad (2)$$

$$Y = \sum_{i=1}^n P_i Y_i / \sum_{i=1}^n P_i \quad (3)$$

$$D_m = \sqrt{(X_{t+m} - X_t)^2 + (Y_{t+m} - Y_t)^2} \quad (4)$$

$$\theta = \arctan \left[\frac{Y_{t+m} - Y_t}{X_{t+m} - X_t} \right] \quad (5)$$

Equations (2) and (3) represent the formulas for the centroid migration model, wherein (X_i, Y_i) represents the geometric centroid of the i th unit within the study area, n is the total number of units in the study area, P_i is the transformation area of unit i , and (X, Y) is the migration centroid of rural settlements within the study area. Equation (4) defines the distance of centroid migration, D represents the distance of the migration of the rural settlement centroid from year t to year $(t + m)$, and (X_t, Y_t) and (X_{t+m}, Y_{t+m}) respectively denote the index centroids of years t and $(t + m)$. Equation (5) defines the angle of centroid migration.

Cold hot spot analysis

The Getis-Ord G_i^* statistic is a common spatial statistical method used to identify hotspots (high-value clusters) and cold spots (low-value clusters) in geographical space⁴⁰. It plays a significant role in analyzing geographical spatial distribution patterns and exploring spatial autocorrelation, possessing advantages such as spatial autocorrelation detection, hotspot and cold spot identification, and statistical significance⁴¹. In this study, administrative villages were used as the basic unit of analysis with the following formula:

$$G_i^* = \frac{\sum_{j=1}^n w_{ij} x_j - \bar{x} \sum_{j=1}^n w_{ij}}{s \sqrt{\frac{n \sum_{j=1}^n w_{ij}^2 - (\sum_{j=1}^n w_{ij})^2}{n-1}}} \times \frac{\bar{x} - \frac{1}{n} \sum_{j=1}^n x_j}{s \sqrt{\frac{n \sum_{j=1}^n w_{ij}^2 - (\sum_{j=1}^n w_{ij})^2}{n-1}}} \quad (6)$$

$$\bar{X} = \frac{1}{n} \sum_{j=1}^n x_j \quad (7)$$

$$S = \sqrt{\frac{1}{n} \sum_{j=1}^n x_j^2 - \bar{x}^2} \quad (8)$$

in Eqs. (6), (7), and (8), n represents the number of spatial grid units, x_i and x_j are the observed values for unit i and unit j respectively, w_{ij} is the spatial weight matrix, and \bar{X} and s represent the mean and standard deviation respectively. A higher G_i^* index value indicates that high-value aggregation in rural settlements is more compact, making it a hotspot for the distribution of rural settlements. A lower G_i^* index value indicates low-value aggregation, representing a cold spot in the spatial distribution of rural settlements. Based on the G_i^* index value, the natural break method is used to divide it into three levels: hotspot areas, unclear areas, and cold spot areas⁴².

Multi-scale geographic weighted regression model

Model principle

The spatiotemporal evolution of rural settlements at the county scale is influenced by natural geography, ecological location, socio-economic factors, and others⁴³. Only by coupling these various influencing factors can we accurately explore the spatial analysis of rural settlements and the scale effects of various aspects. Therefore, this study uses the MGWR model to measure the impact of changes in human production activities on the spatial evolution of rural settlements in the study area from 2010 to 2020, against the backdrop of natural environmental changes and socio-economic restructuring. Compared with other models, the MGWR model can fully consider the changes in each influencing factor at different scales, and better reflect the impact strength and spatial differentiation of each influencing factor on the spatiotemporal evolution of rural settlements. In this study, administrative villages were used as the basic unit of analysis, and Eq. (9) of the MGWR model is as follows⁴⁴:

$$y_i = \beta_o(u_i, v_i) + \sum_{j=1}^p \beta_{bwj}(u_i, v_i) x_{ij} + \epsilon_i, \quad i \in \{1, 2, \dots, n\} \quad (9)$$

in the formula, y_i represents the spatiotemporal changes of rural settlements; x_{ij} denotes the natural environmental factors, locational condition factors, and socio-economic factors that affect the changes in rural settlements; (u_i, v_i) represent the spatial coordinates of sampling point i ; $\beta_o(u_i, v_i)$ indicates the intercept at point i ; $\beta_{bwj}(u_i, v_i)$ represents the regression coefficient of local variables, where a larger absolute value of the regression coefficient implies a greater impact on the spatial distribution of rural settlements; ϵ_i represents random disturbance terms. When determining the optimal bandwidth, the most commonly used quadratic kernel function and Akaike Information Criterion (AIC) method were adopted.

Drive factor selection

Natural geographical conditions significantly influence the development of rural settlements. Excessive slope is not conducive to farming and residential safety, affecting water resource management; settlements are often located

on moderate slopes that facilitate drainage and transportation. Altitude affects climatic conditions, determining crop types and growth cycles, with high-altitude areas potentially suitable for special crop cultivation; terrain fluctuations affect land use efficiency and village layout, with flat areas conducive to agriculture and settlement expansion, while complex terrain promotes adaptive development among residents, such as terraced agriculture. These natural factors collectively shape the spatial distribution, economic activities, and cultural characteristics of rural settlements. In terms of locational conditions, road connectivity promotes the exchange of materials and information between the countryside and the outside world, affecting the direction of settlement expansion and service range; rivers provide water sources, irrigation convenience, and water transport channels, with most rural settlements developing along river belts; train stations, as modern transportation nodes, attract surrounding rural resources to converge, driving the rise of commerce and services, transforming some rural areas into industrial and commercial centers; locational conditions collectively shape the functional layout, economic development, and population distribution patterns of rural settlements, and are important external factors affecting the spatial evolution of settlements. Socio-economic conditions also affect the distribution form and density of rural settlements. In regions with a high level of economic development, settlement scale expands, service facilities improve, attracting population aggregation, and the distribution of rural settlements changes accordingly; industrial structure adjustment promotes the rise and fall of resource-oriented settlements, such as rural settlements in areas rich in minerals or unique tourism resources will be more prosperous; in addition, policy drivers such as new rural construction and urbanization strategies also change the spatial structure of settlements, promoting or inhibiting the development of certain regions, with population density and industrial layout being key driving factors affecting the layout of rural settlements. Therefore, referring to existing research results and combining the current situation of the study area, we selected 15 indicators (Table 1) from natural geography, locational conditions, and socio-economic aspects to construct a model under the premise of ensuring scientificity, to explore the driving role affecting the distribution of rural settlements⁴⁵.

Test for multicollinearity in driving factor features

To prevent the multicollinearity among independent variables from having a negative impact on the model, a multicollinearity test was conducted among the independent variables (Table 2)⁴⁶. The VIF values of per capita cultivated land area (X_{10}), per capita GDP (X_{12}), proportion of primary industry output value (X_{13}), and proportion of secondary and tertiary industry output value (X_{14}) were greater than 7.5, indicating obvious multicollinearity. According to the correlation coefficients of the independent variables (Fig. 3), there is a strong positive correlation between per capita cultivated land area (X_{10}) and per capita GDP (X_{12}), and a strong negative correlation between the proportion of primary industry output value (X_{13}) and the proportion of secondary and tertiary industry output value (X_{14}). Therefore, this study removed the two independent variables of per capita cultivated land area (X_{10}) and the proportion of primary industry output value (X_{13}), and the remaining data will be input into the MGWR model as independent variables⁴⁷.

Level	Driving Factors	Factor Explanation
Physical and geographical conditions	Elevation(X_1)	reflects the vertical zonal distribution pattern of rural residential areas in Xunwu county through the DEM data of Xunwu.
	Slope(X_2)	The slope of Xunwu County is divided through DEM data, exploring the spatial distribution characteristics of rural residential points.
	Terrain Ruggedness(X_3)	Considering the Terrain Ruggedness of Rural Residential Areas.
Location conditions	Road Distance(X_4)	The distance from rural residential areas to main roads, reflecting the convenience of transportation for the distribution of residential areas.
	River Distance(X_5)	The distance from rural residential areas to rivers, reflecting the choice of residential distribution in production and living spaces.
	Passenger Station Distance(X_6)	The distance from rural residential areas to passenger stations, reflecting the convenience of transportation accessibility in the distribution of residential areas.
	Medical facility distance(X_7)	Distance from rural settlement to medical facilities (e.g. hospitals, township health clinics).
	Education facility distance(X_8)	Distance from the main education facility to rural settlements.
Socio-economic conditions	Land Area(X_9)	The total land area of Xunwu Village/km ² , reflecting the total amount of land resources in the region.
	Per Capita Arable Land Area(X_{10})	The ratio of the total arable land area in the village to the total population of the village (mu/person).
	Population Density(X_{11})	The ratio of the total population in a village area to the total land area of the village (people/km ²), reflecting the density of population.
	Per Capita GDP(X_{12})	The ratio of village-level GDP to total population, reflecting the per capita production value within the village area.
	The proportion of primary industry output value(X_{13})	The proportion of primary industry output value in the village area.
	The proportion of secondary and tertiary industry output value(X_{14})	The percentage of the secondary and tertiary industry output value in a village area.
	Grain yield(X_{15})	Total grain yield in village area.

Table 1. Driving force index system.

Driving Factors	2010		2020	
	VIF	1/VIF	VIF	1/VIF
Elevation(X_1)	2.19	0.46	2.10	0.48
Slope(X_2)	6.07	0.16	3.08	0.32
Terrain Ruggedness(X_3)	5.86	0.17	3.09	0.32
Road Distance(X_4)	1.55	0.64	1.55	0.64
River Distance(X_5)	1.25	0.80	1.29	0.77
Passenger Station Distance(X_6)	1.60	0.62	1.57	0.64
Medical facility distance(X_7)	1.99	0.50	1.91	0.52
Education facility distance(X_8)	2.08	0.48	2.14	0.47
Land Area(X_9)	1.90	0.53	1.79	0.56
Per Capita Arable Land(X_{10})	inf	0	inf	0
Population Density(X_{11})	1.29	0.77	1.19	0.84
Per Capita GDP(X_{12})	inf	0	Inf	0
The proportion of primary industry output value(X_{13})	30.46	0.03	11.99	0.08
The proportion of secondary and tertiary industry output value(X_{14})	15.49	0.06	26.96	0.04
Grain yield(X_{15})	2.38	0.42	2.47	0.40

Table 2. Feature multicollinearity test.

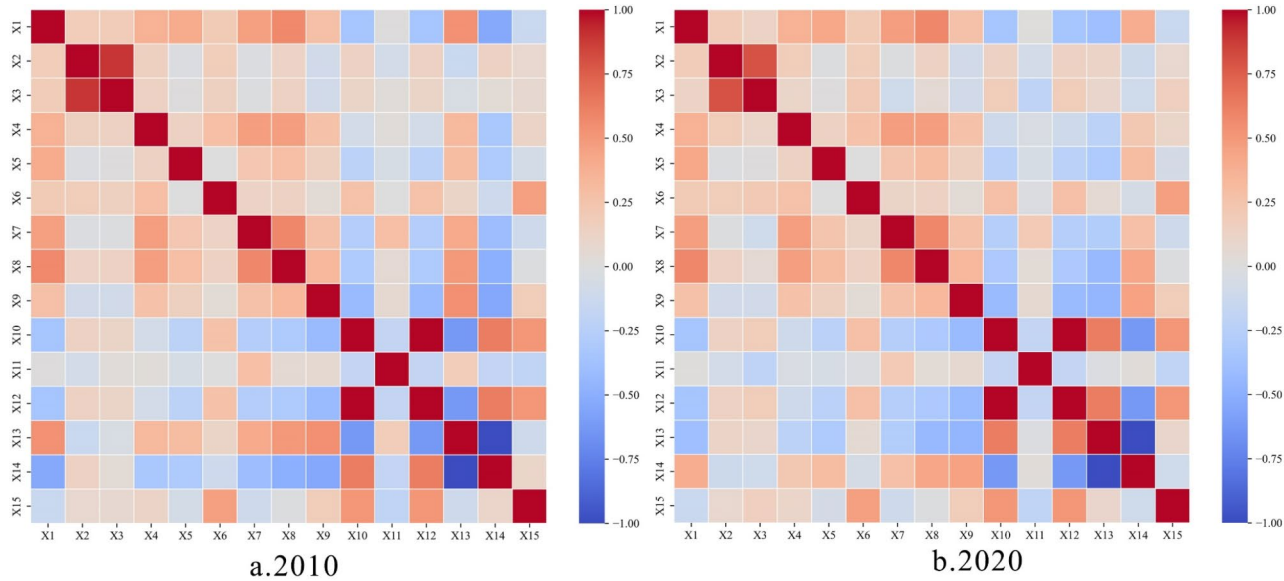


Figure 3. Correlation analysis of independent variables.

Results
Spatiotemporal transformation pattern of rural settlements

Settlement transformation rate
Using the land use data from 2010 as the baseline and that from 2020 as the endline (Fig. 4), we calculated the rate of change in the spatial patches of rural settlements under the dynamic degree of land use. The results show that during the period of 2010–2020, the area of rural settlements in the study region increased by a total of 0.7518 km², showing a gradually increasing trend. The overall change rate was 39.82%, and the dynamic degree was 2.87%.
Looking at the different regions (Table 3), Wenfeng Township has seen the most significant change in rural settlement area, with a decrease of 0.5134 km² and a dynamic degree of 1.95%. This region is located around the city center, and with urban expansion and industrial development, the trend towards urbanization is quite severe. Urban construction land gradually replaces rural settlements, leading to a substantial reduction in settlement area, which is not conducive to rural development. The region with the smallest change in rural settlement area is Longyan Township, with an increase of 0.0182 km² and a dynamic degree of 0.07% (Fig. 5). This region is far from towns, has steep slopes and high altitudes, and has fewer farmers. Over the past decade, there have been no significant changes in the settlements. As can be seen from the figure, areas close to the city center generally show a decreasing trend in rural settlements. These areas are often more susceptible to the impact of urban expansion,

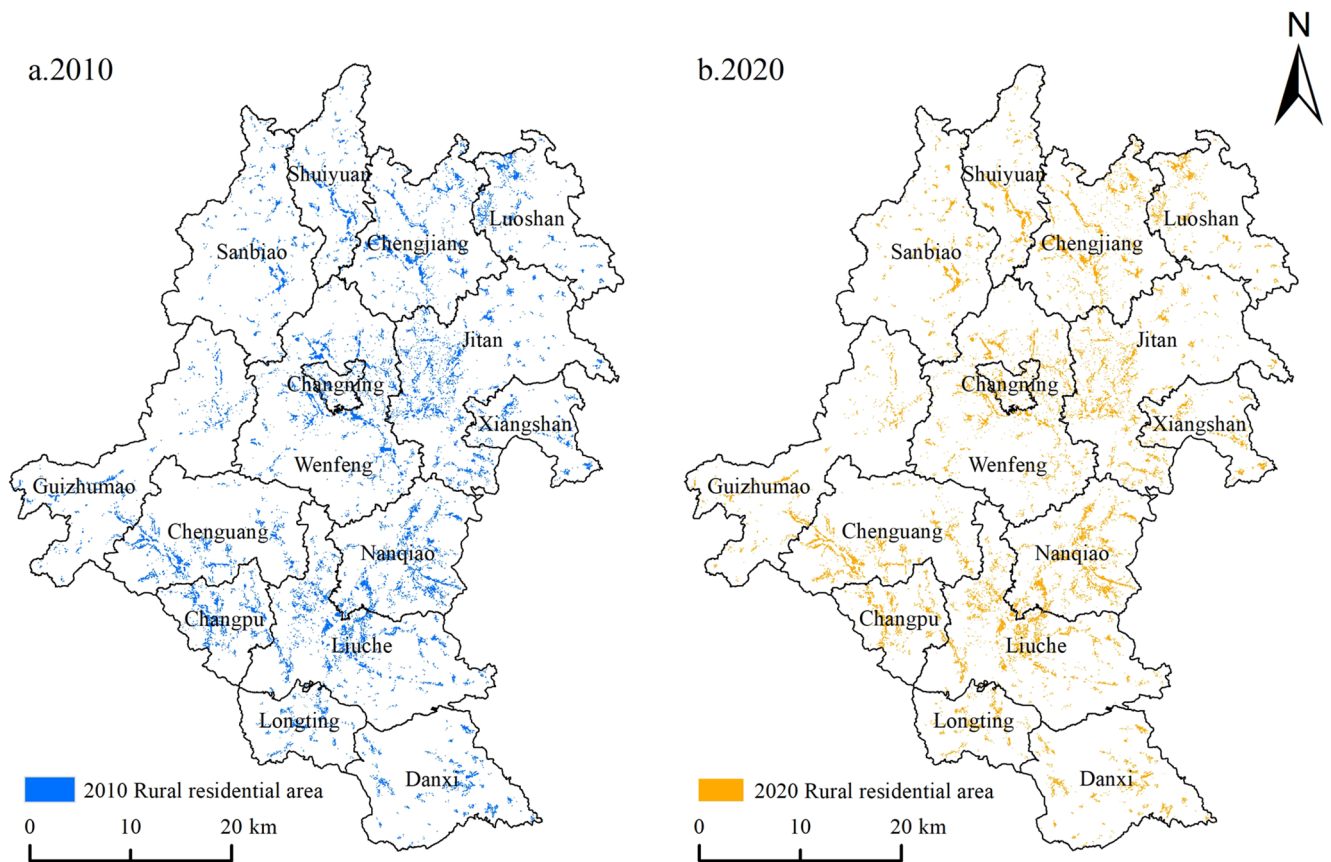


Figure 4. Spatial distribution of rural settlements. (Fig. 4 was generated by the author using ArcMap 10.2 software. The vector data of rural settlements were extracted from LandsatTM/ETM remote sensing images in Geospatial data cloud (<http://www.gscloud.cn/>). Software version number is 10.2, links to <https://desktop.arcgis.com/>).

leading to continuous outward expansion of the city's edge. Settlements in nearby areas may be transformed into urban construction land due to urbanization, resulting in a reduction or even disappearance of the original rural settlement area. On the other hand, due to factors such as agricultural development, population migration, and policy orientation, areas far from cities have improved levels of agricultural modernization, promoting the development of primary industries. The scale of rural settlements has expanded, but their overall dispersion has also increased.

Transition path analysis

The centroid migration model was used to analyze the migration path of the centroid of Xunwu rural settlements from 2010 to 2020. Analyzing the migration path of the centroid of Xunwu rural settlements is beneficial for exploring the migration process and direction of rural settlements. As can be seen from the map of the centroid migration path of Xunwu rural settlements (Fig. 6), the average centroid of Xunwu rural settlements from 2010 to 2020 was located in Wenfeng Township, with an overall migration direction towards the southeast, and a migration distance of 3.7 km. The migration results indicate that the main growth area of Xunwu rural settlements is located in the southeast direction of Xunwu. The underlying reason is that over the past decade, the development speed of towns and townships in the southeast direction of Xunwu has been faster than other areas, such as Nanqiao Town, Liuche Town, and Longting Township, where the increase in residential area ratio is all greater than 30%, far exceeding the increase in residential area ratio in other townships.

Overall, the centroid of residential areas in 2010 and 2020 were both located in Wenfeng Township, indicating that the overall changes in Xunwu's residential areas from 2010 to 2020 were relatively small, with a stable overall pattern. The underlying reason may be that Xunwu's terrain is typical of hilly mountainous areas, which has certain regional restrictions on its development speed and space. Wenfeng Township has a large land area, with a smaller proportion of mountainous land, and a wide distribution of residential areas. This is another reason why the centroid of residential areas is located in Wenfeng Township.

Analysis of spatial patterns in cold and hot spots

In this study, the administrative villages in Xunwu County were used as the basic unit of analysis. By analysing the unit spatial values of hotspots and coldspots of rural settlements in the study area from 2010 to 2020, and then according to the degree of aggregation of rural settlements, the villagers' rural settlements were classified

Region/Area	Changpu	Chenguang	Chengjiang	Danxi	Guizhumao	Jitang	Liuche	Longting	Luoshan	Nanqiao	Sanbiao	Shuiyuan	Wenfeng	Xiangshan	Changning
2010/km ²	1.67	1.99	2.57	1.15	1.25	2.89	3.40	0.64	1.26	2.5	1.2	1.13	3.39	0.75	0.27
2020/km ²	1.38	2.36	2.99	1.55	1.09	2.40	3.36	0.66	1.17	3.05	1.59	1.32	2.88	0.77	0.34
Dynamic attitude	1.11%	1.38%	1.62%	1.54%	0.61%	1.84%	0.16%	0.07%	0.35%	1.83%	1.37%	0.72%	1.95%	0.09%	0.26%

Table 3. Rural settlement transformation rate.

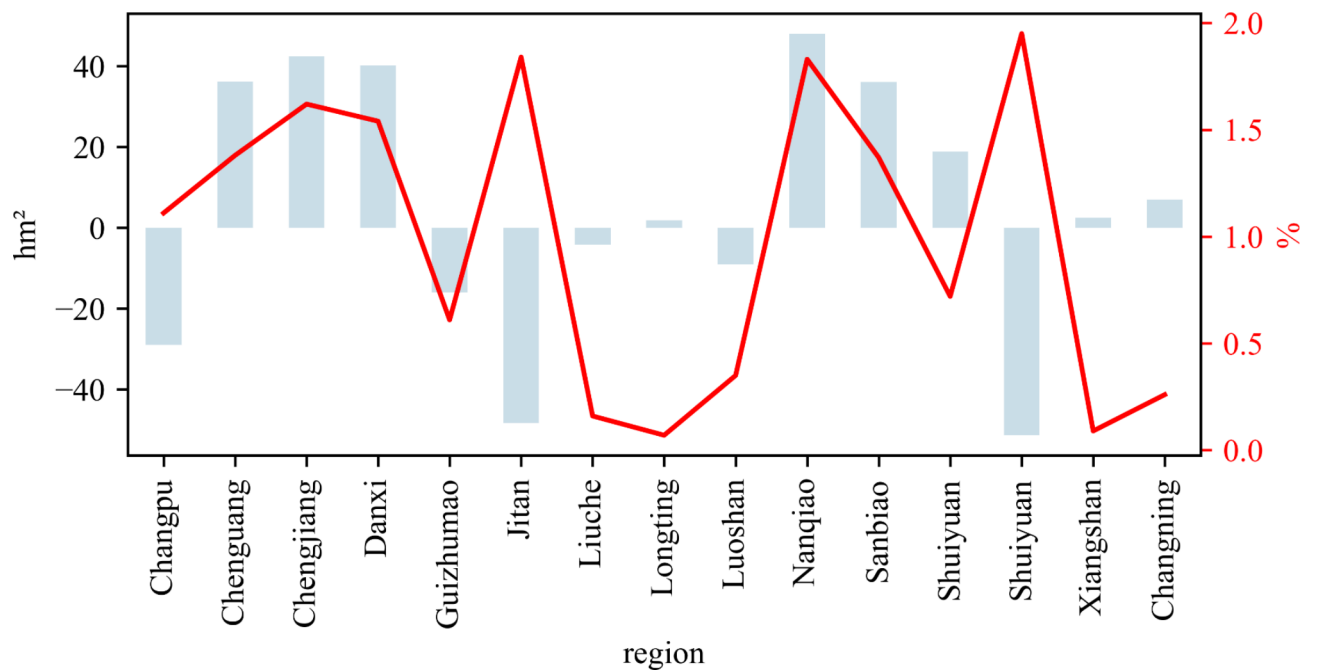


Figure 5. Regional transition rate diagram.

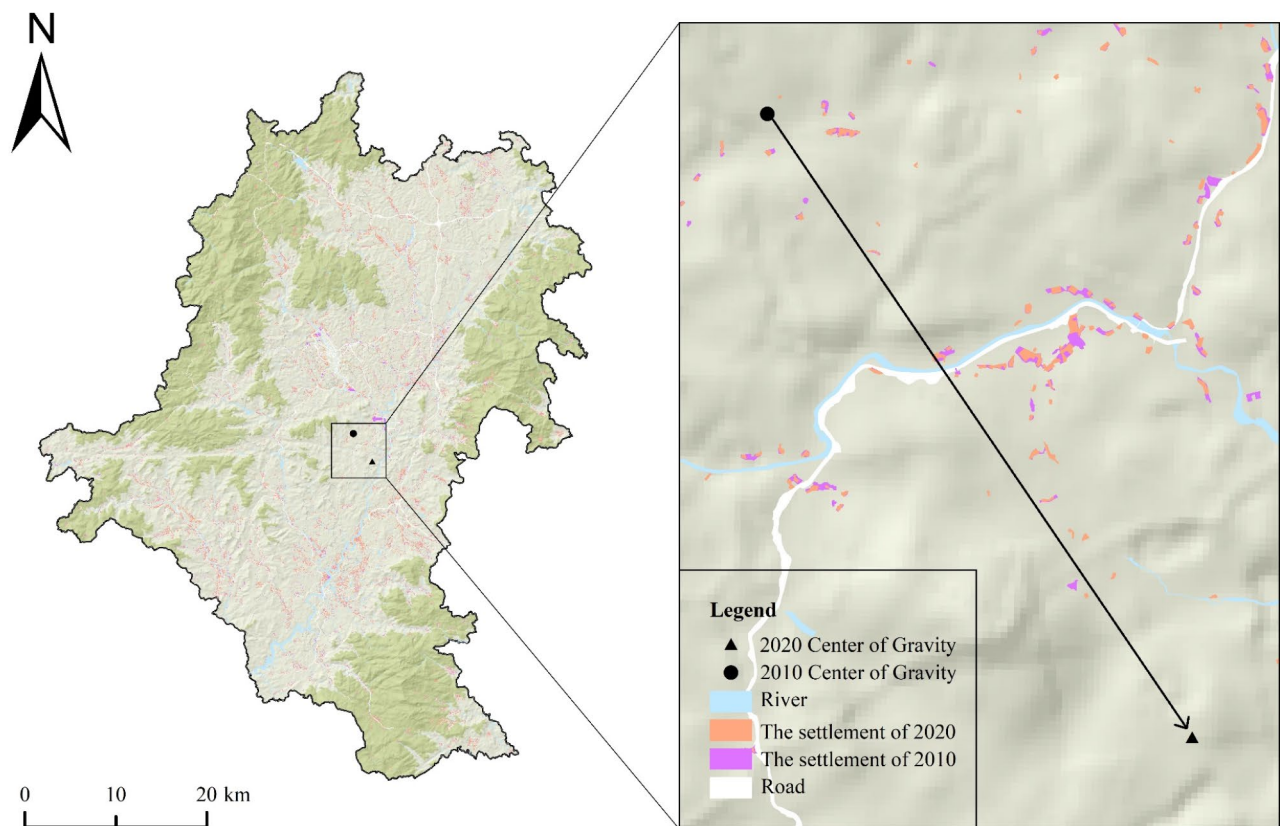


Figure 6. Center of gravity migration path. (Fig. 6 was generated by the author using ArcMap 10.2 software. Township software version number is 10.2, links to <https://desktop.arcgis.com/>).

into hotspots, cold spots and non-significant areas (Fig. 7). The hotspot areas of rural settlements in Xunwu in 2010 were: the southern part of Wenfeng Township, the northwest part of Jitan Town, the northeast and southwest parts of Chengjiang Town, and the northeast part of Guizhumao Town; the cold spot areas of rural settlements in Xunwu in 2010 were: the southeast part of Luoshan Township, the west part of Sanbiao Township, the northeast part of Guizhumao Town, and the west and central parts of Chenguang Town; all other areas were non-significant. The hotspot areas of rural settlements in Xunwu in 2020 were: most villages in Chengjiang Town, the southeast part of Shuiyuan Township, the northwest part of Luoshan Township, the northwest part of Jitan Town, and the central part of Nanqiao Town; the cold spot areas of rural settlements in Xunwu in 2020 were: the southeast part of Luoshan Township, the northeast part of Jitan Town, the northern part of Sanbiao Township, the east part of Guizhumao Town, and the central part of Chenguang Town; all other areas were non-significant.

Overall, the hotspot distribution of rural settlements in Xunwu has changed significantly from 2010 to 2020, shifting from the central townships of Xunwu to the northern and some southern townships. This is partly due to the moderate altitude and environmental conditions that meet basic living and production needs. On the other hand, over the past decade, infrastructure such as roads and medical facilities in Xunwu have been continuously improved, greatly enhancing the convenience of people's lives. In the process of location selection, residents also tend to choose areas with comprehensive facilities and convenient living conditions.

Driving mechanisms of rural settlement transformation

Driving factor diagnosis results

The area of rural settlements in 2010 and 2020 was taken as the dependent variable, and the relevant indicators of natural geographical conditions, locational conditions, and socio-economic conditions were taken as independent variables. The data were input into the GWR and MGWR models respectively, and the diagnostic information of the two models was obtained (Table 4). The higher the values of R^2 and Adj. R^2 , and the lower the values of AICc and Sigma-Squared, the better the performance of the model. The modeling results show that compared with the GWR model, the MGWR model has higher values of R^2 and Adj. R^2 , and lower values of AICc and Sigma-Squared, demonstrating better performance.

The GWR uses a fixed bandwidth in each calculation, 86 in 2010 and 95 in 2020. In contrast, the MGWR generates a separate optimal bandwidth for each independent variable in each calculation (Table 5). This indicates that the MGWR better reflects the scale effects of different influencing factors. The greater the difference between the bandwidth and the global scale, the stronger the spatial heterogeneity. In MGWR, factors such as elevation

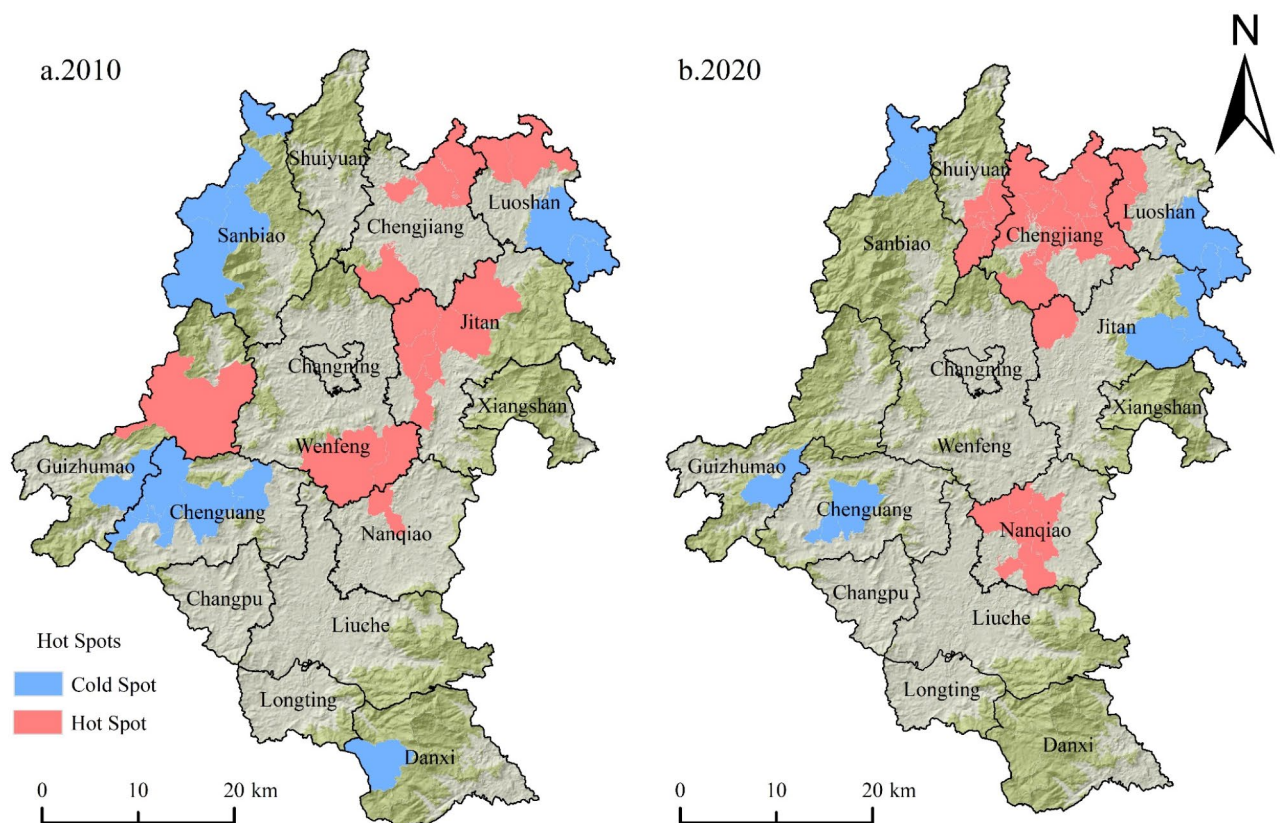


Figure 7. Spatial patterns in cold and hot spots. (Fig. 7 was generated by the author using ArcMap 10.2 software. Township software version number is 10.2, links to <https://desktop.arcgis.com/>).

Year	2010		2020	
Model	GWR	MGWR	GWR	MGWR
R ²	0.79	0.84	0.65	0.76
Adj. R ²	0.73	0.80	0.57	0.70
AICc	312.60	261.79	389.65	343.75
Sigma-Squared	0.27	0.20	0.43	0.30

Table 4. Diagnostic information of GWR and MGWR.

Factors	2010		2020	
	Adjacent Elements (Element Percentage)	Significant (element percentage)	Adjacent Elements (Element Percentage)	Significant (element percentage)
X ₁	96 (54.55)	72 (40.91)	31 (17.61)	53 (30.11)
X ₂	142 (80.68)	0 (0.00)	176 (100.00)	0 (0.00)
X ₃	176 (100.00)	0 (0.00)	86 (48.86)	19 (10.80)
X ₄	176 (100.00)	0 (0.00)	142 (80.68)	0 (0.00)
X ₅	38 (21.59)	47 (26.70)	56 (31.82)	0 (0.00)
X ₆	64 (36.36)	19 (10.80)	176 (100.00)	0 (0.00)
X ₇	123 (69.89)	134 (76.14)	176 (100.00)	176 (100.00)
X ₈	176 (100.00)	176 (100.00)	176 (100.00)	0 (0.00)
X ₉	30 (17.05)	111 (63.07)	30 (17.05)	58 (32.95)
X ₁₁	152 (86.36)	0 (0.00)	137 (77.84)	27 (15.34)
X ₁₂	50 (28.41)	176 (100.00)	48 (27.27)	176 (100.00)
X ₁₄	109 (61.93)	176 (100.00)	31 (17.61)	162 (92.05)
X ₁₅	73 (41.48)	176 (100.00)	176 (100.00)	176 (100.00)

Table 5. Summary of explanatory variables and adjacent elements in the MGWR Model. Note: Best GWR bandwidth (neighbouring features): 86 (2010), 95 (2020). The numbers in parentheses for the neighbouring features range from 0 to 100% and can be interpreted as local, regional and global scales based on geographical backgrounds from low to high; the numbers in italic parentheses represent the percentage of features with significant ($P < 0.1$) coefficients of explanatory variables.

(X₁) in natural geographical conditions, river distance (X₅) in locational conditions, land area (X₉), per capita GDP (X₁₂) in socio-economic conditions have larger differences from the global scale of 176, with more drastic parameter changes, demonstrating stronger spatial heterogeneity. The significant coefficient elements of slope (X₂) in natural geographical conditions and road distance (X₄) in locational conditions account for 0, indicating that these two factors do not have significant impacts in this region, suggesting their influence is quite weak in this area.

Driving mechanism

Figures 8 and 9 show the local regression results of MGWR in 2010 and 2020, respectively. In natural geographical conditions, the negative impact of elevation factor (X₁) was enhanced in the northeast region, but it turned into a positive impact in some areas of Chengjiang and its surroundings, which may be due to the expansion of rural clusters towards high-altitude areas with regional development. Terrain roughness (X₃) showed a positive impact in Sanbiao in 2020. The influence of locational conditions was weakening overall because the effects of river distance (X₅), passenger station distance (X₆), and educational facility distance (X₈) factors had become globally insignificant in 2020. The negative impact range of medical facility distance (X₇) factor expanded to the global scale, which may be related to aging. Compared with the first two conditions, the influence range and degree of socioeconomic conditions were larger than those of the previous two. The influence range of land area (X₉) factor was shrinking, and the influence degree was slightly weakened. Population density (X₁₁) factor changed into a slight negative impact in the northwest. Per capita GDP (X₁₂) factor had a large negative impact, but it weakened in the northern region. The proportion of secondary and tertiary industry output value (X₁₄) factor changed from a global positive impact to a negative impact in a larger area, which may be related to industrial structure adjustment. Grain yield (X₁₅) always showed a strong global positive impact, which may be due to the fact that this region is dominated by agriculture. Therefore, socioeconomic conditions dominate the rural clustering area of this region, followed by locational conditions whose influence is weakening, and finally natural geographical conditions with localized impacts.

Finally, we determine the evolution mechanism of mountainous rural settlements based on the main influencing factors (Fig. 10). We find that the interaction of socio-economic factors has the most significant driving effect on the evolution of rural settlements. Land area (X₉) and grain yield (X₁₅) form a positive driving force for evolution, while population density (X₁₁), per capita GDP (X₁₂), and the proportion of secondary and tertiary industry output value (X₁₄) form a negative driving force. The negative driving force is mainly

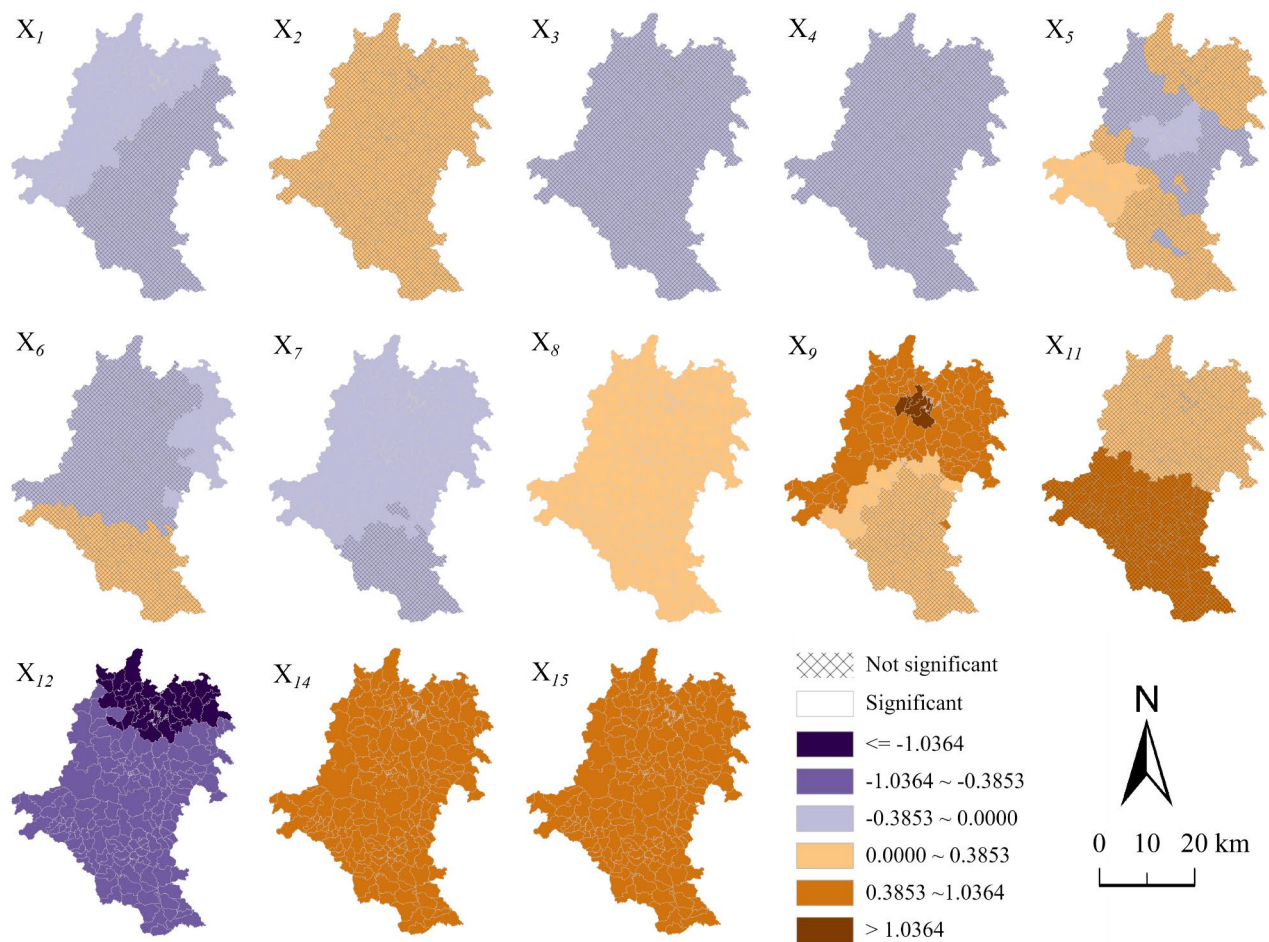


Figure 8. Spatial distribution of factor regression coefficients in 2010. (Fig. 8 was generated by the author using ArcMap 10.2 software. Township software version number is 10.2, links to <https://desktop.arcgis.com/>).

related to economic development, indicating that the higher the level of economic development, the more the rural settlements are shrinking. This may be caused by the siphon effect of urban areas on rural areas, with rural settlements in decline. The negative driving force may be due to local industrial characteristics; Xunwu is an agricultural county, and the agricultural production in this region has a high demand for population. Therefore, agricultural production requires more rural settlements as production guarantees. The factor of medical facility distance (X₇) in location conditions continues to have a negative driving effect on evolution. Natural geographical conditions have more obvious spatial heterogeneity and jointly affect the evolution of rural settlements with other factors, especially in the northern region.

Discussion

Comparative analysis of findings with existing literature

Our study's findings both align with and differ from previous research on rural settlement evolution, offering new insights into the complex dynamics of settlement patterns in mountainous regions. While our results corroborate some general trends observed in existing literature, they also reveal unique patterns and relationships specific to the mountainous context of Xunwu County.

In line with many previous studies, our research confirms the dominant role of socioeconomic factors in shaping rural settlement patterns. However, our findings diverge from some existing research regarding the influence of locational conditions. While many studies have emphasized the crucial role of road accessibility in settlement development, our results indicate that the influence of such locational factors, including road distance, has weakened over time in Xunwu County^{48,49}. This difference may be attributed to improved infrastructure in our study area, which has reduced the impact of location on settlement development. Our multi-scale approach using the MGWR model has allowed us to capture spatial heterogeneity in the impacts of natural factors, particularly the varying effects of elevation and terrain roughness across different regions of Xunwu County. This level of detail is often absent in studies employing single-scale models, underscoring the importance of considering scale effects in rural settlement studies, especially in mountainous areas with complex topography⁵⁰. The observed migration of settlement hot spots from central townships to northern and southern areas in our study area aligns with trends noted in some previous research⁵¹. However, while many studies attribute

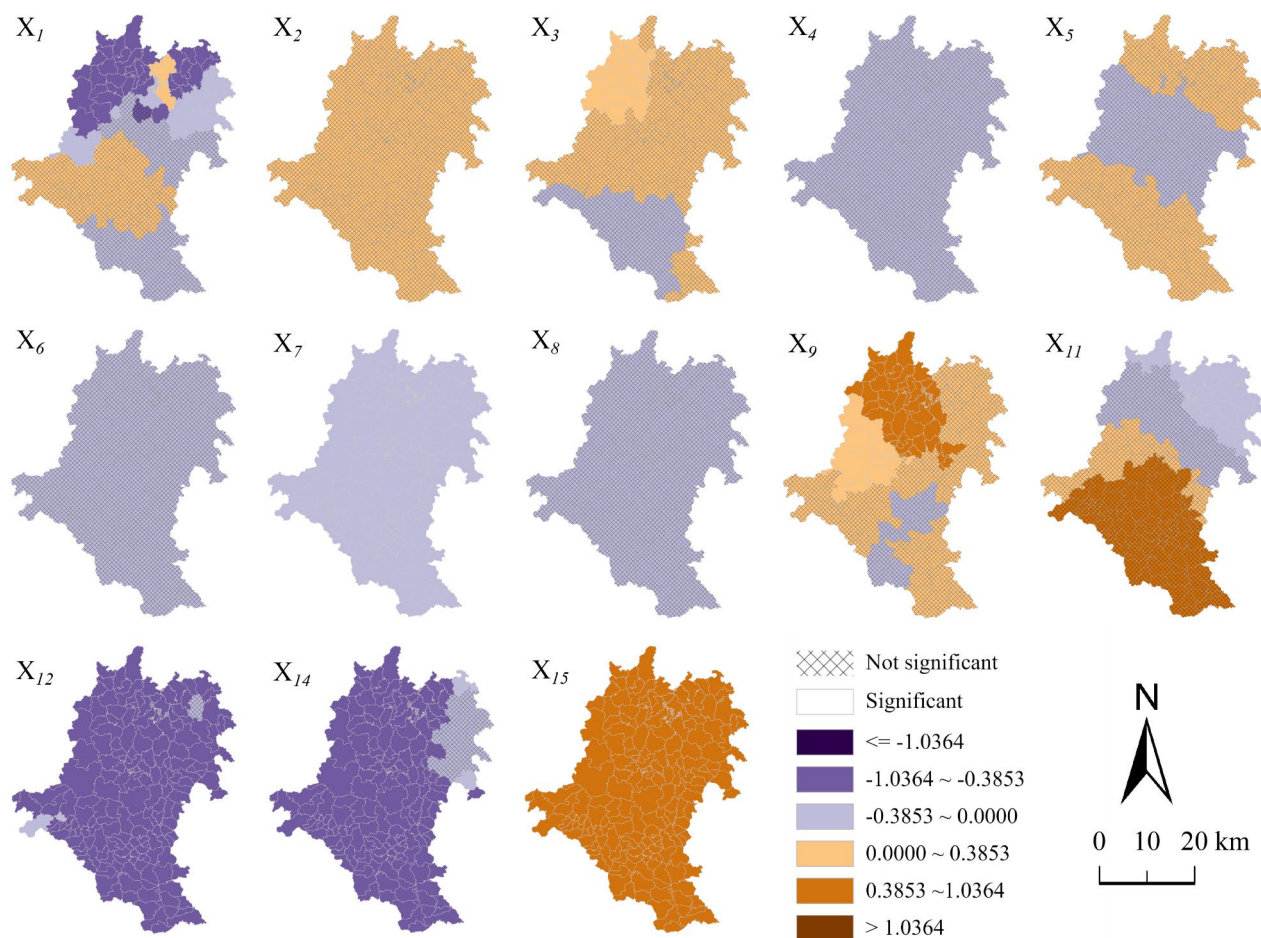


Figure 9. Spatial distribution of factor regression coefficients in 2020. (Fig. 9 was generated by the author using ArcMap 10.2 software. Township software version number is 10.2, links to <https://desktop.arcgis.com/>).

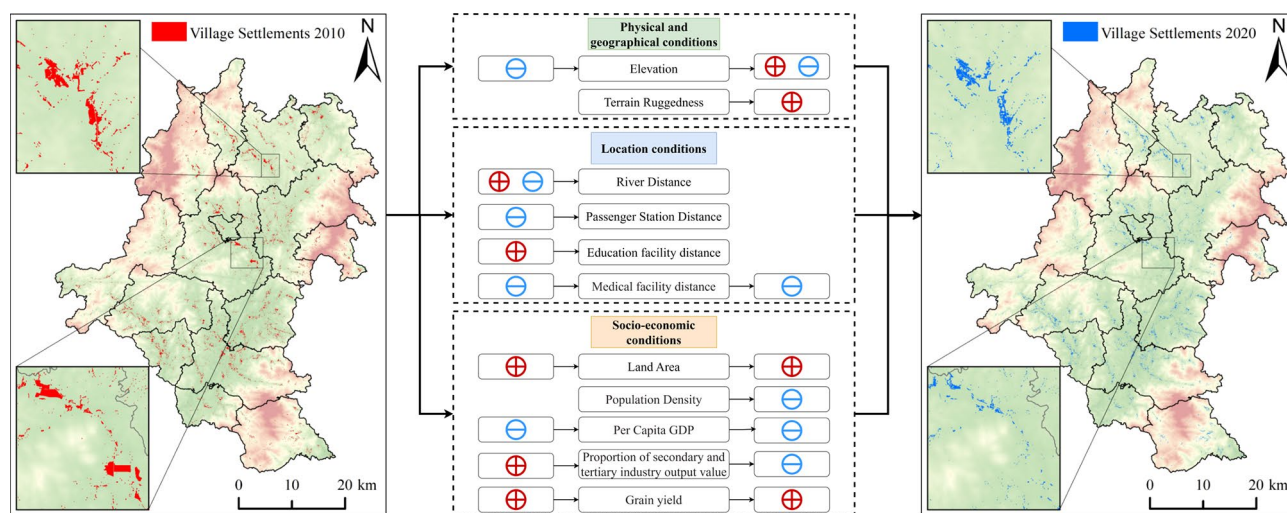


Figure 10. Evolution mechanism of rural settlements in 2010 and 2020. The red + sign indicates positive driving, and the blue - sign indicates negative driving. (Fig. 10 was generated by the author using ArcMap 10.2 software. Township software version number is 10.2, links to <https://desktop.arcgis.com/>).

such shifts primarily to government policies promoting balanced regional development, our results suggest a more complex interplay of factors, including natural conditions, infrastructure improvements, and economic restructuring. Our finding of a weakening influence of river proximity on settlement patterns contrasts with some existing research that reports strong correlations between river networks and rural settlement distribution. This difference likely reflects the varying importance of water resources in different geographical contexts, with our mountainous study area possibly less dependent on river access for agricultural and residential purposes⁵². The strong positive impact of grain yield on rural settlements observed in our study is consistent with findings from other agricultural regions. However, our MGWR model revealed spatial variations in this relationship, with some areas showing a weaker correlation. This nuanced understanding highlights the need for spatially differentiated rural development strategies, even within regions with similar economic structures⁵³.

These comparisons demonstrate that while our study corroborates some general findings from previous research, it also reveals unique patterns and relationships specific to the mountainous context of Xunwu County. Our multi-scale approach and comprehensive consideration of various factors contribute to a more nuanced understanding of rural settlement evolution, emphasizing the importance of place-specific analysis in informing sustainable rural development policies.

Spatiotemporal pattern changes in rural settlements

This paper reveals the significant spatial pattern changes in rural settlements of Xunwu County from 2010 to 2020 through the centroid migration model and hot-spot analysis. The path of the centroid migration of rural settlements shows that the distribution of settlements gradually shifted from central townships to some northern and southern townships, which is closely related to the suitability of natural geographical conditions, improvements in infrastructure, and adjustments in economic activities. For example, the terrain in the northern townships is relatively flat, suitable for agricultural production and residents' living. In addition, the continuous improvement of infrastructure such as roads and medical facilities in the past decade has enhanced the attractiveness of these areas, promoting the expansion of settlement scale and population aggregation. The hot-spot analysis shows that the changes in hot-spot areas reflect the dynamism and selectivity of settlement development, which are usually matched with the level of economic development, transportation convenience, and suitability of natural conditions. For instance, the southern part of Wenfeng Township and the northwest part of Jitan Town were hot-spot areas in 2010, possibly due to the tapping of economic development potential, attracting more resource investment, leading to further expansion of settlement scale. However, cold-spot areas like the southeast part of Luoshan Township may be limited in settlement development due to remote geographical location, inconvenient transportation, and relatively backward economy. By 2020, the northward shift of hot-spot areas indicates that under the joint action of government support and market forces, the infrastructure and economic conditions of northern townships have improved, promoting population return and concentrated development of settlements.

Complex mechanism of rural settlement evolution

The spatiotemporal evolution of mountainous rural settlements is a complex process, and its geographical specificity manifests at multiple levels⁵⁴. Natural geographical conditions, especially elevation and terrain undulation, exhibit significant spatial heterogeneity in different regions⁵⁵. For example, the negative impact of elevation in the northeast region is enhanced, which may be related to steep terrain and inconvenient transportation, while the positive impact of high-altitude areas in the Chengjiang region indicates that economic development and infrastructure improvement may have promoted settlement expansion with regional development⁵⁶. In addition, the evolution of locational conditions has also affected settlement evolution, although the proximity of rivers, passenger stations, and educational facilities has weakened its impact on settlement evolution, which may reflect that the popularization of services has reduced the differences in locational advantages⁵⁷. Socioeconomic conditions play a dominant role in rural settlement evolution, where land area and grain yield act as positive driving factors, interacting with negative driving factors such as population density, per capita GDP, and the proportion of secondary and tertiary industry output value to jointly determine the evolutionary direction of rural settlements⁵⁸. Areas with higher levels of economic development are often accompanied by the shrinkage of rural settlements, which may be due to the siphon effect of towns on villages⁵⁹. At the same time, the fundamental role of agricultural production cannot be ignored, and the positive impact of grain yield reflects the core position of agriculture in the development of mountainous rural settlements⁶⁰. Aging issues and medical facility layout have also affected the evolution of rural settlements. The negative impact of medical facility distance has expanded to a global scale, which may be related to aging issues in mountainous areas, posing new requirements for the layout of service facilities in rural settlements⁶¹. In addition, the coupling of economic development and geographical environment plays a decisive role in rural settlement evolution, where natural conditions such as terrain and elevation limit the potential for economic development while also affecting the distribution and accessibility of residential points. In summary, the spatiotemporal evolution of mountainous rural settlements is jointly influenced by natural geographical conditions, locational conditions, and socioeconomic conditions⁶². The geographical specificity of these factors requires us to consider their interactions and regional differences when formulating rural development planning and policies to comprehensively assess the complexity of spatiotemporal evolution of rural settlements, promote sustainable development of rural settlements, and balance urban-rural development gaps.

Limitations and future research directions

Although the MGWR model provides an effective tool for analysing spatial heterogeneity, there is still the possibility of estimation bias, especially when the sample points are unevenly distributed or the amount of data is insufficient. In addition, the selection of explanatory variables may be influenced by the subjective

judgement of the researcher, and factors not included, such as managerial decisions and cultural traditions, may also have an important impact on settlement evolution. Managers need to develop and implement land use plans to ensure the sustainable development of rural settlements. This includes determining the proper layout of agricultural land, residential land, commercial land and land for public facilities, as well as protecting the natural environment and cultural heritage⁶³. On the other hand, managers need to decide how to invest in infrastructure, such as roads, water supply, drainage, and electricity systems, to ensure that the infrastructure of rural settlements meets the needs of residents and supports economic development. Future research should consider adding more dimensional variables to improve the comprehensive explanatory power of the model and assess the complexity of the spatio-temporal evolution of rural settlements more comprehensively through interdisciplinary approaches, such as combining theories from sociology, economics and ecology. In addition, the use of long-term tracking data and multi-case comparative studies will further validate the universality and specificity of the current findings and provide a more solid foundation for sustainable development strategies for rural settlements⁶⁴.

Conclusion

This study explores the spatiotemporal evolution pattern and internal driving mechanism of Xunwu rural settlements from 2010 to 2020 through single land use dynamic degree, centroid migration model, spatial hot and cold spot analysis, and multi-scale geographic weighted regression model. The following conclusions were drawn:

- (1) From 2010 to 2020, the area of rural settlements in Xunwu increased by 0.7518 km², with an overall change rate of 39.82%, and a land use rate of 2.87%. Among them, Wenfeng Township experienced the largest increase in area, benefiting from its geographical location advantage, proximity to the county urban center, relatively developed economy, high population concentration, and the growth of rural settlements radiating outward from the city center.
- (2) The direction of the major relocation of rural settlements in Xunwu from 2010 to 2020 was southeast, with a migration distance of 3.7 km. Overall, the center of gravity remained relatively stable, located in Wenfeng Township. In 2010, the hotspot areas of rural settlements were in the southern part of Wenfeng Township, the northwest of Jitan Town, the northeast and southwest of Chengjiang Town, and the northeast of Guizhumao Town; by 2020, the hotspot areas had shifted to most villages in Chengjiang Town, the southeast of Shuiyuan Township, the northwest of Luoshan Township, the northwest of Jitan Town, and the central region of Nanqiao Town.
- (3) From 2010 to 2020, the driving mechanisms of rural settlements in Xunwu are as follows: From the perspective of natural geographical conditions, the negative impact of elevation (X_1) in the northeastern region has increased, but in some areas of Chengjiang and its surroundings, it has turned into a positive impact. This may indicate that rural clusters have begun to expand towards high-altitude areas, and the terrain undulation (X_3) showed a positive impact in Sanbiao in 2020; From the perspective of locational conditions, the distance to rivers (X_5), passenger stations (X_6), and educational facilities (X_8) have become globally insignificant, while the negative impact of medical facility distance (X_7) has expanded to the global scale; From the perspective of socio-economic conditions, the influence range and degree of socio-economic conditions are much higher than those of natural geographical conditions and locational conditions. Among them, grain yield (X_{15}) always has a strong driving effect on rural settlements, possibly because the economic structure of the study area is dominated by agriculture. Overall, socio-economic conditions play a dominant role in driving rural settlements, the influence of locational conditions has declined, and the impact of natural geographical conditions is minimal.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions

Zexu Chen: Writing – original draft, Methodology, Formal analysis, Data curation. Huachun Dong: Supervision, Methodology, Funding acquisition, Conceptualization.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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