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Research article

Spatial pattern characteristics and influencing factors of mountainous rural settlements in metropolitan fringe area: A case study of Pingnan County, Fujian Province

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A B S T R A C T

Amid global industrialization and urbanization, mountainous rural settlements, especially those in metropolitan fringe area, are experiencing significant spatial changes in location and scale. This study takes Pingnan County, Fujian Province, China, as an example. Utilizing land use data and employing methods including standard deviation ellipse, average nearest neighbor index, kernel density estimation, spatial hotspot detection, binary logistic regression model, and Geodetector, this study aims to scientifically identify the spatial pattern characteristics and influencing factors of its settlements. The results show that: (1) The spatial distribution of settlements in Pingnan County is biased toward the southern part of the county; the center of settlement's spatial distribution is located south of the junction of Gufeng Town and Pingcheng Town; the spatial distribution trend of settlements is north-east-southwest. Settlements are generally aggregated, and the aggregation degree of Gufeng Town is obviously lower than that of other towns. (2) The density distribution of settlements presents a "core-periphery" structure and a "north-south linear" structure in space; the spatial pattern characteristics show high-density, large patches in Gufeng Town, high-density, small patches in Changqiao Town, Tangkou Town and Gantang Town, and medium-density or low-density, small patches in other towns. (3) Settlement location is mainly affected by the elevation, distance to cultivated land, and distance to main roads, while settlement scale is mainly affected by slope, relief degree of land surface, and distance to urban centers. The interaction between these factors exhibits enhancement effects, with natural terrain and location conditions exerting the most prominent influence. These findings underscore the strong constraints posed by natural topography on mountainous rural settlements in metropolitan fringe areas, coupled with a more pronounced influence from socio-economic factors. The study's results hold significant implications for optimizing the layout of such settlements, guiding land spatial planning, and promoting rural revitalization.

1. Introduction

Rural settlements can be defined as places of various forms where humans live in rural areas with agricultural activities as the main industry and agricultural population as the main residents [1]. Rural settlements are also central places for human activities with

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multiple functions such as production, life, ecology, and culture [2]. For thousands of years before the industrial revolution, rural settlements have been the main social form of human beings. Since the end of World War II, rapid global industrialization and urbanization have strongly impacted rural settlements. The lag and decline of rural settlement development have become a global problem in globalization. For example, developed regions such as the United States, Canada, and Europe are facing problems such as urban-rural gap, concentrated poverty, cultural conflicts, and irrational use of land [3,4], while developed and developing countries such as Africa and India are facing problems such as serious land degradation, widespread poverty, and food insecurity [5]. It has become a common consensus of mankind to scientifically understand the development law of rural settlements and promote the sustainable development of rural settlements [6,7].

China is a large agricultural country with a sizable rural population. Statistics show that in 2021, 5.0979×10^8 people still live in rural areas, accounting for about 36.11% of the total population, although this is a marked drop from the 8.70×10^8 people in the 1990s [8,9]. China is also a mountainous country, with mountainous areas accounting for about 70% of the country's land area [10]. County-level administrative units in mountainous areas constitute approximately half of China's total, yet their urbanization levels are far below the national average [11]. Nevertheless, 45% of the Chinese population still lives in mountainous areas, and rural settlements in mountainous areas are an important form of settlement for Chinese people. In the process of urbanization in China, the large-scale migration of rural population has caused huge spatial changes in the location and scale of settlements, especially in mountainous areas [12]. For a long time, natural attributes like topographic gradient, surface fragmentation and spatial isolation have decisively shaped mountainous settlements [13], establishing a historical pattern dependent on topography, hydrology, and arable land. Under the rapid urbanization, mountainous settlements generally suffer from imperfect infrastructure, socio-economic marginalization and massive population loss due to the constraints of natural environment. Their developmental lag behind plains poses a hindrance to the construction of new urbanization, rural transformation, and the coordinated development of urban and rural areas [14]. Therefore, clarifying the spatial pattern characteristics and influencing factors of mountainous rural settlements is not only the theoretical basis for rationally planning the layout of settlements, but also a practical problem that needs to be solved for the efficient promotion of the rural revitalization strategy.

Scholars around the world have been concerned about rural settlements for a long time, with early research emerging in the 1920s when German and French human geographers conducted extensive research on settlements in rural areas. Initial studies employed field surveys and mapping, qualitatively summarizing relevant laws using theories of typology, morphology, and phenomenology [15]. In recent decades, research has paid more attention to the application of quantitative analysis methods, such as RS, GIS, landscape pattern index, spatial measurement methods, multiple regression Geodetector, resulting in more refined and scientific outcomes. These research delve into various aspects such as the number, density, scale, morphology, evolution patterns, influencing factors, driving mechanisms, typology, spatial optimization, and scenario prediction of rural settlements. For instance, Clark et al. explored the spatial distribution characteristics of rural settlements in distant suburbs of the United States and the factors related to their spatial configurations [16]; Yang et al. investigated the spatial distribution characteristics of rural settlements in China amid rapid urbanization and explored optimization and reconstruction patterns [17]; Ristic et al. analyzed the impact of the spatial distribution characteristics of rural settlements on tourism development in Serbia [18]; Duan et al. analyzed the phenomenon of dispersed and fragmented distribution of settlements in mountainous areas of western Henan Province, China [12]. These analyses of the spatial patterns of rural settlements increase our knowledge of the distribution of rural settlements and our understanding of the relationship between people and land. They serve as crucial guidance for rural planning initiatives. Related studies also show that topography, hydrology, climate, transportation, and socio-economic factors strongly influence rural settlement distribution [19]. For example, Wu et al. argue that settlements in the hilly mountainous areas of Jiangnan tend to be concentrated in the low mountain basins and river valley terraces [20], Guo and Li suggest that settlements in the Loess Plateau region show strong topographic, river, and transportation orientations [21,22]. Li et al. find settlements in the karst mountainous areas of Southwest China mainly clustered along transportation routes [23], and Yang et al. highlight road accessibility's vital role in Guangzhou's rural settlement distribution [2]. It can be seen that the influencing factors of the spatial pattern of settlements may be different in different regions, and the influential power of the influencing factors is also different. At the same time, with the continuous progress of socio-economic conditions and the development of technology, the role of natural conditions in constraining rural settlements is gradually weakening, while the influence of socio-economic factors, such as roads and urban centers, is becoming more diversified and stronger. Through the literature review, we found that, (1) compared to the more developed areas in eastern China [24] and the lagging regions in central and western China, where agricultural policies are more beneficial [25], little attention has been paid to mountainous rural settlements in metropolitan fringe area. Unlike general rural settlements, these areas exhibit heightened susceptibility to the influence of developed cities, resulting in intricate and diverse spatial characteristics. (2) existing analyses of rural settlements often adopt a singular perspective, predominantly focusing on either density or aggregation. Comprehensive analyses considering multiple indicators remain limited. (3) previous studies investigating influencing factors typically treat settlements as mere points, neglecting their inherent area attributes. Settlements, however, extend beyond point-like entities, with varying sizes influenced by the amalgamated effects of multiple factors. Hence, it is imperative to integrate area attributes into the exploration of the intricate relationships between settlements and influencing factors.

Pingnan County, Fujian Province, situated in the southeast of China, exemplifies a typical metropolitan fringe area characterized by widespread hills and mountains, boasting the highest average altitude in Fujian province. For a long time, a notable developmental divide has persisted between mountainous and coastal areas in Southeast China. Economic and demographic concentrations in more favorably located coastal areas have resulted in a pronounced lag in the industrialization and urbanization of inland mountainous zones. Furthermore, the influence of coastal cities has led to a sharp population decline in mountainous areas, prompting significant differentiation and reorganization of rural settlements. In view of this, this paper employs various methods, like standard deviation ellipse, average nearest neighbor index, kernel density estimation, spatial "hot spot" analysis, binary logistic regression model, and Geodetector, to analyze settlements spatial pattern, including the characteristics of the spatial distribution, degree of agglomeration, density, and scale. Then, 10 indicators reflecting the regional natural environment, resource endowment, transportation and location are utilized to identify influencing factors. The study aims to furnish a practical foundation for optimizing and regulating mountainous rural settlements in metropolitan fringe area, offering crucial insights for the development of mountainous counties and rural revitalization.

2. Materials and methods

2.1. Study area

Pingnan County is located in Ningde City, Fujian Province, China, covering 1487 km^2 (26°44′–27°10′N, 118°41′–119°13′E), including 11 townships and 153 administrative villages (Fig. 1). It is situated in Jiufeng Mountains, with an average altitude of 830 m, and the terrain is high in the northwest and low in the southeast. Pingnan County is a typical inland mountainous county with mountainous area accounting for 81%. It is within the mid-subtropical marine monsoon climate, with an annual average temperature of 13–18 °C, with summer without heat and winter without cold. The difference in temperature between the day and night is large, showing obvious characteristics of alpine climate. It has abundant rainfall with an annual precipitation of 1842.3 mm and an average annual relative humidity of 83%. There are 186 rivers in Pingnan County, divided into two major water systems, Huotong River and Gutian River, with an average annual runoff of 1.746 billion m^3, and an average annual evapotranspiration of 575–725 mm. The main soil types in Pingnan County include red soil, accounting for 46.8%, and yellow soil, accounting for 34.46%. Additionally, the county features purple soil, tidal soil, and paddy soil. The vegetation in Pingnan County is subtropical broad-leaved forest, mainly evergreen broad-leaved forest, cedar willow forest, moso bamboo forest, oleander forest, etc., with a forest coverage rate of 76.8%. Crop types in Pingnan County are mainly rice and vegetables, such as cauliflower, celery, eggplant, and cucumber. By the end of 2020, the resident population of Pingnan County was 139,815, a decrease of 16.97% compared with 168,389 in 2000. In the past decade, Pingnan County has adjusted its industrial structure, transformed and upgraded its agricultural production, adjusted the proportion of its three industries from 15.29 : 34.35: 50.36 in 2021 to 21.60 : 40.15: 38.25 in 2012, and withdrawn from the list of key counties of provincial poverty alleviation and development work. Scientific revelation of the spatial pattern characteristics and influencing factors of its settlements is conducive to precise governance and planning, and promotes regional rural development.

2.2. Data sources

The data used in this study mainly include land use type data, elevation data, annual temperature and precipitation data, and geographical element data. (1) Land use type data comes from the global 10 m land cover product of the Gong Peng team (FROM-GLC10, 10 m, 2017) [26]; (2) elevation data were extracted from the 2009 L-band ALOS PALSAR (2006–2011) radar data with a 12.5 m spatial resolution provided by NASA (https://search.asf.alaska.edu); (3) temperature and precipitation data were sourced from the Data Centre for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (https://www.resdc.cn/); (4) Pingnan County administration boundary, road data, river data, and urban center data were obtained from National Catalogue Service For

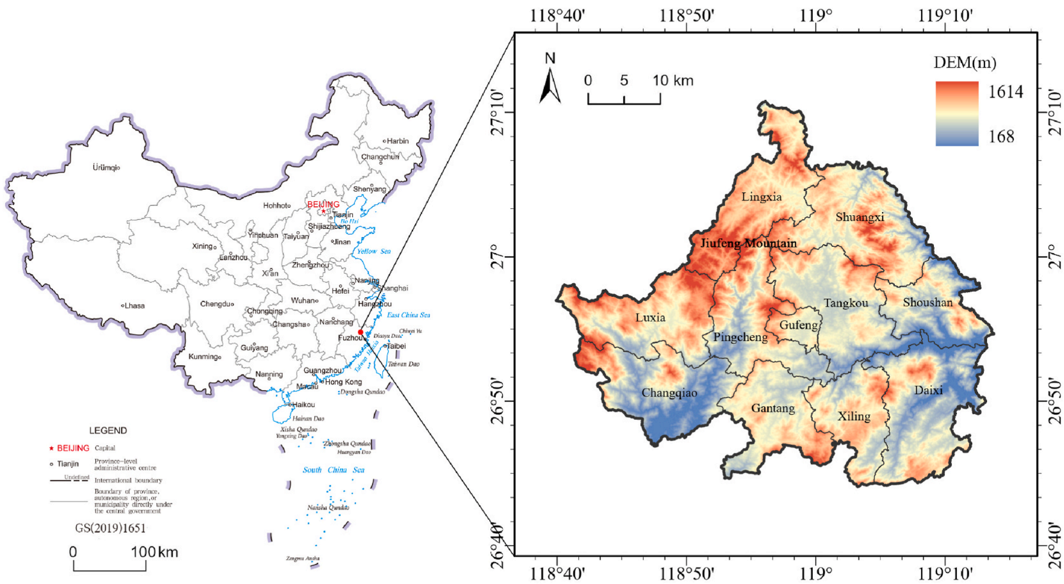

Fig. 1. Location of study area.

Geographic Information (https://www.webmap.cn/).

2.3. Methods

2.3.1. Standard deviation ellipse (SDE)

The standard deviation ellipse can accurately reveal the central trend, dispersion and direction trend of geographic elements, and it is a spatial statistical method for quantitatively analyzing the overall characteristics of the spatial distribution of geographic elements. The direction of the major axis of the ellipse represents the main distribution direction of geographical elements; the center of the ellipse reflects the relative position of the overall spatial distribution of the elements in two-dimensional space. The length of the major axis of the ellipse represents the extent to which the spatial distribution of elements deviates from the center of gravity in the main direction, and the minor axis represents the degree of deviation from the center of gravity in the secondary direction. The ratio of the major axis to the minor axis can reflect the shape of the spatial distribution of elements [27].

2.3.2. Average nearest neighbor index (ANN)

The average nearest neighbor index is the ratio of the average distance between a point and its nearest point and its expected value of the point in the study area under the assumption of a random distribution to judge the relationship between the geographical elements [28,29]. Its calculation formula is:

$$ANN = \frac{\overline{D_0}}{\overline{D_e}} = \frac{\sum_i d_i \Big/ n}{\sqrt{n/A} \Big/ 2} = \frac{2\sqrt{\lambda}}{n}\sum_i d_i \tag{1}$$

where $\overline{D_0}$ is the average distance between two closest elements; $\overline{D_e}$ is the average distance between the two elements under the assumption of random distribution; n is the total number of elements; d is the distance between elements; A is the area of the study area. If ANN = 1, the element distribution pattern is random; if ANN<1, the element distribution tends to be aggregated; if ANN>1, the element distribution tends to be discrete.

2.3.3. Kernel density estimation (KDE)

The kernel density estimation is a nonparametric density estimation method. It assumes that geographic events can occur anywhere in space, but the probability of occurrence in different locations is different. The probability of events occurring in areas with dense points is high, and the probability of events occurring in areas with sparse points is low [30]. This method can be used to calculate the density of points in the surrounding area, and can show where the points are more concentrated.

2.3.4. Spatial "hot spot" analysis

The Getis-Ord Gi* index can be used to test whether there are statistically significant high and low values in local areas, and use regional visualization methods to reveal hot spots and cold spots, and then analyze their local autocorrelation [31]. Z (Gi*) can well reflect the hot and cold distribution of observations in the local space area, and its calculation formula is:

$$G_i^* = \sum_{j=1}^{n} W_{ij}(d_i)X_i \Big/ \sum_{j}^{n} X_j \tag{2}$$

where $W_{ij}(d)$ is the spatial weight between area i and j; X_j is the attribute value of area j, and n is the total number of areas.

2.3.5. Binary logistic regression model

The binary logistic regression model is a nonlinear classification statistical method used in the regression analysis of the binary dependent variable (dependent variable takes the value 1 or 0) [32]. The model formula is as follows:

$$\ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots\cdots + \beta_n x_n \tag{3}$$

where p represents the probability of event occurrence; x_n represents the influencing factors; β_0 is a constant term; β_n is the regression coefficient of the variable.

2.3.6. Geodetector

Geodetector is a set of statistical methods that detect the spatial variability of geographic elements or geographic phenomena and reveal their driving forces [33]. The core idea is based on the assumption that if an independent variable has an important impact on a dependent variable, the spatial distribution of the independent and dependent variables should be similar. Geodetector can not only detect the driving force of a single factor, but also compare the driving force of interaction of two factors [34]. The magnitude of the driving forces is measured by the q statistic, which physical meaning is that the independent variable explains (100 × q)% of the dependent variable. This method is mathematically represented as follows:

$$q = 1 - \frac{1}{N\sigma^2}\sum_{h=1}^{L} N_h \sigma_h^2 \quad (4)$$

where L is the number of classifications for a certain factor; N_h and σ_h are the number of units and variance in layer h respectively; N and σ are the number of units and variance of the study area respectively; the value range of the q value is [0, 1], and larger the value indicates greater influence of the independent variable on the dependent variable.

2.4. Research framework

The methodological framework of this study is shown in Fig. 2, which consists of three steps: (1) data collection encompasses the land use data, elevation data, temperature and precipitation data, road data, river data, and urban center data. (2) data processing involves calculations for settlement patches, elevation, slope, annual average temperature, distance to rivers, etc. (3) data analysis unfolds through various methods: 1) SDE, ANN, KDE and Spatial "hot spot" analysis are used to obtain center, range and direction of distribution, concentration characteristics, density distribution characteristics, scale, and density distribution characteristics, respectively. 2) binary logistic regression model examines the correlation between settlement locations and influencing factors. Before regression, the land use data undergoes (0, 1) binarization, designating 1 for grid cells with settlements and 0 for those without. Over 50,000 sampling points in Pingnan County are randomly generated through ArcGIS Pro 3.0.1. Subsequently, these points undergo dimensionless processing in SPSS 26 for regression analysis. 3) Geodetector examines the correlation between settlement scale and influencing factors. As the dependent variable is numerical and the independent variable is typological, the study adopts a 500 m × 500 m grid cell for scale statistics. The values of independent variables (influencing factors) are discretized using a classification method combining expert experience and the natural breakpoint method, followed by modeling operations.

3. Results

3.1. Spatial pattern characteristics of settlements

This paper uses SDE, ANN, KDE and spatial "hot spot" analysis to comprehensively describe the spatial pattern characteristics of settlements in Pingnan County.

SDE can describe center, range and direction of settlements' spatial distribution. The SDE in Pingnan County is biased towards the south of the county, mainly covering Gufeng Town, Pingcheng Town, Tangkou Town, Gantang Town, Xiling Town, and northeast of Changqiao Town. The center of settlements' spatial distribution is located south of the junction of Gufeng Town and Pingcheng Town. The major axis of SDE extends from northeast to southwest, roughly in the same direction as the ridge of Jiufeng Mountain. The major axis is 16.578 km long and the minor axis is 14.753 km long. The difference between them is not large, indicating that the distribution of settlements in Pingnan County has central characteristics (Fig. 3).

ANN can reveal the concentration characteristics of settlements' spatial distribution. According to the ANN calculation formula, the ANN value at the county scale is $0.303 < 1$, and the corresponding P value < 0.01, Z score < -2.58, and degree of confidence is 99%,

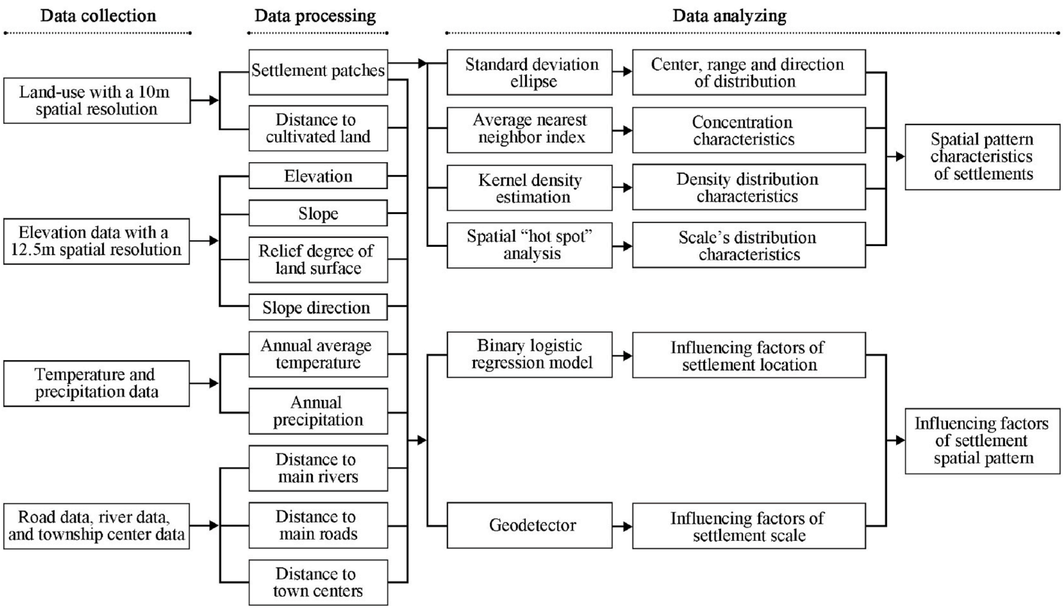

Fig. 2. Methodological steps taken in the study.

indicating that settlements in Pingnan county are generally aggregated. The ANN values at the town scale are all less than 1, and all pass the 1% test, indicating that the settlements in various towns are also aggregated, but the aggregation of settlements of each town has regional differences. There are 5 towns whose ANN value is lower than the overall level of the county, i.e., the aggregation is more obvious, and 6 towns whose ANN value is higher than the overall level of the county, i.e., the degree of aggregation is relatively small. Among them, the ANN value of Gufeng Town, administrative center of the county, is 0.514, which is significantly higher than that of other towns, indicating that the degree of aggregation of Gufeng Town is lower than that of other towns. The ANN values of Shuangxi Town, Daixi Town, Changqiao Town, Luxia Town and Pingcheng Town are all less than 0.3, indicating that the aggregation is more obvious (Table 1).

KDE and spatial "hot spot" analysis can further analyze the characteristics of the spatial pattern of settlements in Pingnan County. The kernel density distribution of settlements in Pingnan County presents a "core-periphery" structure and a "north-south linear" structure in space. In addition, the kernel density in the southern region is higher than that in the northern region. The high-density area is distributed in double belts, with a value of 7.921–17.116 per km^2, one is a belt extending from Tangkou Village in Tangkou Town to Gantang Village in Gantang Town, and the other is a belt extending north-south with Changqiao Village as the core. The medium-density area mainly expands outward around the high-density area, and some areas are distributed in a dot-like manner in the southern region of Pingnan County, with a value of 3.089–7.920 per km^2. The low-density area is relatively vast, especially in the northeast and northwest of Pingnan County. Then, the study creates 500 m × 500 m grids covering Pingnan County, and uses the settlement area as a variable to carry out spatial "hot spot" analysis, which aims to explore the distribution characteristics of the settlement scale. The results show that the hotspots present an "isolated island shape", mainly concentrated in and around the administrative center of the county, and the rest are scattered in administrative center of Changqiao Town, Luxia Town, Shuangxi Town, Tangkou Town, etc. And cold spot areas are widely distributed (Fig. 3). Combining the results of KDE and spatial "hot spot" analysis, the spatial pattern characteristics of Pingnan County show high-density, large patches in Gufeng Town, high-density, small patches in Changqiao Town, Tangkou Town and Gantang Town, and medium-density or low-density, small patches in other towns.

3.2. Influencing factors of settlement spatial pattern

The settlement spatial pattern is essentially the result of the coupling of regional natural factors and human factors. Pingnan County is a typical high-altitude mountainous county, and the mountainous environment is also a major factor limiting the formation and development of settlements. In general, people tend to build settlements in areas with lower elevations and gentle terrain. Moreover, variations in sunshine hours and solar radiation intensity create warm, dry conditions on sunny slopes and cold, wet conditions on

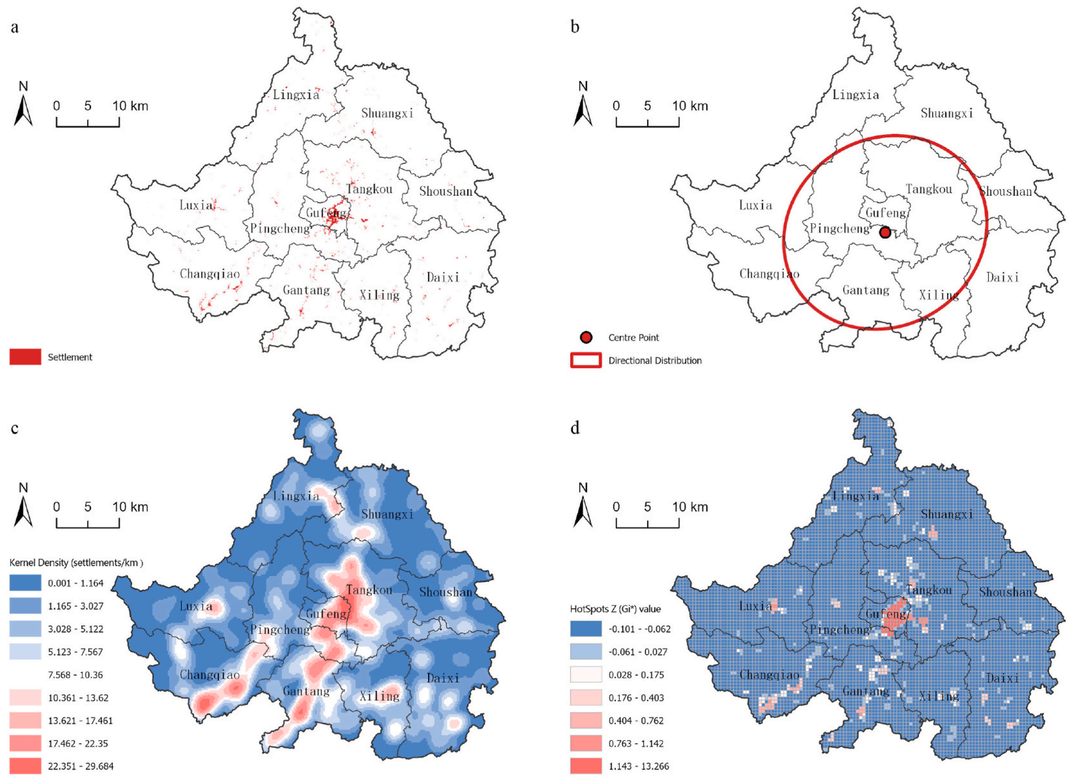

Fig. 3. Spatial pattern characteristics of settlements in Pingnan County. Fig. 3a is distribution of rural settlement patches. Fig. 3b is SDE of rural settlement patches. Fig. 3c is KDE of rural settlement. Fig. 3d is spatial "hot spot" analysis of rural settlement.

Table 1
The ANN of settlements in Pingnan County.

Rank	Region	ANN	Z	P	Rank	Region	ANN	Z	P
–	County	0.303	−113.563	0.00	6	Changqiao	0.284	−42.955	0.00
1	Gufeng	0.514	−18.172	0.00	7	Luxia	0.272	−27.707	0.00
2	Pingcheng	0.296	−37.986	0.00	8	Lingxia	0.326	−29.279	0.00
3	Tankou	0.334	−46.292	0.00	9	Shuangxi	0.267	−30.548	0.00
4	Xiling	0.342	−27.881	0.00	10	Shoushan	0.311	−20.120	0.00
5	Gantang	0.356	−41.731	0.00	11	Daixi	0.267	−33.820	0.00

shady slopes in mountainous areas, potentially correlating with the spatial distribution of settlements based on slope orientation. The complex geomorphologic types in Pingnan County contribute to substantial spatial and temporal variations in multi-year precipitation and average temperature, significantly impacting the primary industry. Agriculture, historically the backbone of livelihoods in Pingnan County, grapples with limited arable land, making water resources and cultivation radius pivotal factors shaping the spatial pattern of rural settlements. Furthermore, transportation and location merit consideration. In mountainous areas, topography shapes transportation routes, fostering connectivity between urban and rural areas. Settlements cluster along roads of varied grades. Cities and towns, central to public service provision, profoundly impact economic and social development. Considering these factors and the accessibility of data, this study has condensed 10 index factors reflecting topographical conditions, meteorological conditions, resource endowment, and transportation location: elevation (x_1), slope (x_2), relief degree of land surface (x_3), slope direction (x_4), annual average temperature (x_5), annual precipitation (x_6), distance to cultivated land (x_7), distance to main rivers (x_8), distance to main roads (x_9), and distance to urban centers (x_{10}), to analyze influencing factors of settlement spatial pattern. The main roads include expressways, national roads, provincial roads, and county roads.

3.2.1. *Influencing factors of settlement location*

The binary logistic regression model was used to analyze the correlation between settlement locations and influencing factors. The results found that the significance of slope direction (x_4) is at the 0.05 level, and the other factors are all at the 0.01 level. The binary logistic regression model is as follows:

$$\ln\left(\frac{p}{1-p}\right) = -1.031x_1 - 0.674x_2 - 0.908x_3 - 0.147x_4 - 0.697x_5 - 0.116x_6 - 1.212x_7 - 0.055x_8 - 1.145x_9 - 0.605x_{10} - 7.466$$

where the coefficient of elevation (x_1), distance to cultivated land (x_7), distance to main roads (x_9) are larger, indicating that settlement locations in Pingnan County is greatly affected by these three factors, and settlements tend to be distributed in areas with lower altitudes, closer to cultivated land, and closer to roads. Slope (x_2), relief degree of land surface (x_3), annual average temperature (x_5), distance to urban centers (x_{10}) are the secondary influencing factors affecting settlement location.

3.2.2. *Influencing factors of settlement scale*

Geodetector is used to detect the spatial pattern of settlement scale and influencing factors in this study. In influencing factor, lope direction (x_4) was divided into 8 categories of N (0–22.5°, 337.5–360°), NE (22.5–67.5°), E (67.5–112.5°), EN (112.5–157.5°), N (157.5–202.5°), WN (202.5–247.5°), W (247.5–292.5°), WN (292.5–337.5°). The rest of the variables are divided into 8 levels by natural breakpoint method. Then, relevant variables were input into the model, and the determination power *q* value and significance level *p* value of each influencing factor were obtained (Table 2).

The results show that the significance of distance to main rivers (x_8) is at the 0.05 level, and the other factors are all at the 0.01 level, showing a significant correlation. Slope (x_2), relief degree of land surface (x_3) and distance to urban centers (x_{10}) have a greater impact on the spatial pattern of settlement scale, indicating that natural factors and location conditions jointly affect the settlement scale. The settlement scale is larger in places with small slopes, small relief degrees of land surface, and close distances to urban centers. Elevation (x_1), distance to cultivated land (x_7), distance to main roads (x_9), annual average temperature (x_5), and annual precipitation (x_6) also determine settlement scale to a certain extent. Nevertheless, slope direction (x_4) as well as distance to main rivers (x_8) have little influence on settlement scale.

On the basis of single factor detection, the value of interaction between influencing factors is detected, which is reflected on the map in linear and equal intervals by heat map in Origin (Fig. 4). Study found that the *q* value of interaction between influencing factors was greater to varying degrees compared with single factor effects. The interaction type is dominated by nonlinear enhancement.

Table 2
Results of factor detection for settlement scale in Pingnan County.

Factor	q statistic	p value	Factor	q statistic	p value
x_1	0.0290	0.000	x_6	0.0166	0.000
x_2	0.0459	0.000	x_7	0.0228	0.000
x_3	0.0495	0.000	x_8	0.0024	0.016
x_4	0.0028	0.002	x_9	0.0195	0.000
x_5	0.0161	0.000	x_{10}	0.0453	0.000

Among them, the q value of $x_1 \cap x_{10}$ is the largest, which is 0.171, indicating that elevation and distance to urban centers are the dominant influencing factors affecting settlement scale. The lower the elevation and the closer to the urban centers, the larger the settlement scale. The q values of $x_1 \cap x_2$、$x_1 \cap x_3$、$x_2 \cap x_{10}$、$x_3 \cap x_{10}$ are all above 0.13, indicating that the interaction among elevation, slope, relief degree of land surface and distance to urban centers have greater roles in promoting settlement scale. The q value of $x_2 \cap x_5$、$x_2 \cap x_6$、$x_3 \cap x_5$、$x_3 \cap x_6$、$x_2 \cap x_9$、$x_3 \cap x_9$、$x_5 \cap x_{10}$、$x_6 \cap x_{10}$ are all above 0.10. It can be seen that the slope, relief degree of land surface, annual average temperature, annual precipitation and distance to main roads have a greater enhancement effect when they interact with other factors. The q value of $x_4 \cap x_8$ is the smallest, and the interaction type is two-factor enhancement, indicating that the enhancement effect of slope direction and distance to main rivers on settlement scale is relatively weak. In addition, x_2, x_3, x_{10} interact most frequently in the interaction with q value greater than 0.10, which further reflected the important role of slope, relief degree of land surface and distance to urban centers on settlement scale. Overall, the spatial pattern of settlement scale in Pingnan County is mainly driven by natural terrain and regional accessibility.

Further, based on the above main influencing factors, the specific distribution pattern of the settlements was counted. It is found that, in terms of topographic conditions, settlements in Pingnan County are mostly distributed in the region with altitudes of 806–906 m and slopes of less than 13.6°, and the area of settlements in this region is more than 231 km^2, accounting for more than 86.7%, while settlements are mostly distributed in the region with relief degree of land surface of less than 6 m, and the area of settlements in this region is 195.37 km^2, accounting for 73.3%. In terms of meteorological conditions, the settlements are mostly distributed in the region with an average annual temperature of 15.8–16.3 °C and an average annual precipitation of 2023–2053 mm, and the area of the settlements in the region accounts for 67.5%. In terms of resource endowment, settlements are mostly located in areas with 0–313.2 m distance from cultivated land, and the area of settlements accounts for 81.9%. In terms of transportation location, the settlements were mostly distributed in the region with the distance of 0–798.3 m from main roads, and the area of settlements accounted for 90.26%. The settlements were also mostly distributed in the region with the distance of 0–2519.8 m from urban centers, and the area of settlements accounted for 79.22%.

4. Discussion

4.1. Analysis of spatial pattern characteristics and influencing factors of settlements

At present, numerous empirical case studies reveal a directional pattern in the distribution of settlements. Due to the special characteristics of the geographic and socio-economic environment, the spatial pattern characteristics and influencing factors of mountainous rural settlements in metropolitan fringe area are more complicated. We try to analyze the causes and processes of formation of this pattern through the understanding of natural and socio-economic environment. Firstly, the natural environment lays the initial state and foundation of the spatial pattern of settlements. On the whole, mountains play a decisive role in the spatial pattern of settlements in Pingnan Country. Affected by the layout and direction of the Jiufeng Mountains, settlements in Pingnan Country tend to

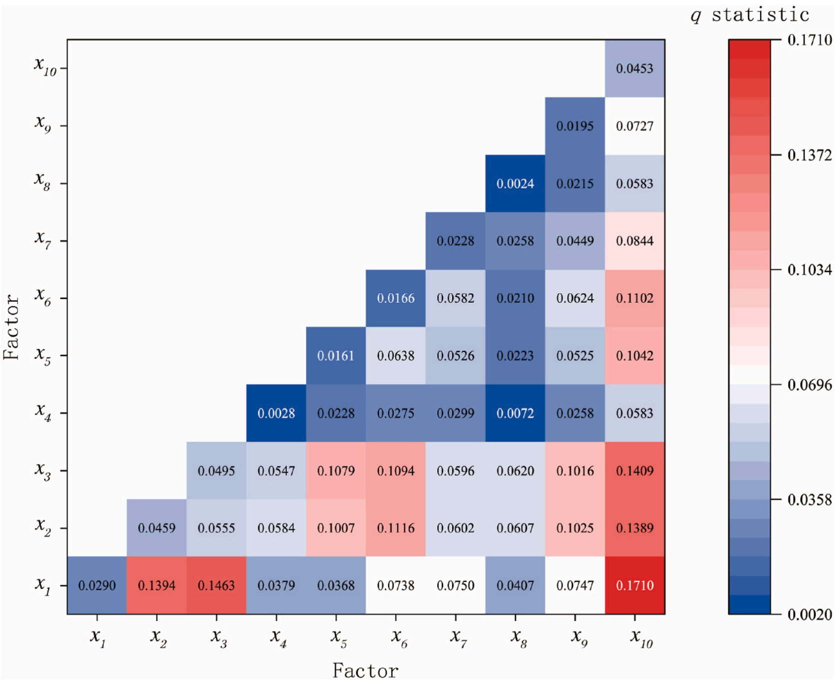

Fig. 4. Results of factor interaction detection results for settlement scale in Pingnan County.

be dispersed over an extensive area with localized concentrations in relatively flat terrain. The north-south orientation of the Jiufeng Mountains also makes settlements present a significant “north-south linear” structure, and settlements tend to gather in the south of the county. Secondly, socio-economic environment played a key role in the later development of settlement. From the previous analysis, we can see that the density of settlements around the county seat is extremely high, which is a relatively flat area. The radiation effect of the town on the distribution of rural settlements is significant, which promotes the aggregation of settlements around county seat, thus presenting a “core-periphery” structure. This is also a contemporary pattern formed after the rapid urbanization of Pingnan County.

Furthermore, we delve into specific influencing factors contributing to the formation of settlements. Regarding settlement location, elevation, distance to cultivated land and distance to main roads emerge as paramount considerations. Settlements predominantly favor medium and low altitude (809–906 m), offering advantages like accessible irrigation and agriculture, population movement facilitation, efficient transportation, and reduced exposure to natural disasters [24,35]. The availability of arable land is crucial for production and life. In general, the spatial distribution of settlements within the farmland system in the plains is uniform, and the intensification of arable land is significant, making it easier to integrate land resources than in mountainous areas [36]. However, land suitable for agricultural production in mountainous areas is scarce and dispersed because of topographical constraints, and the radius of cultivation is larger than in plains areas. Consequently, people prioritize areas with gentler slopes for farming over constructing buildings. Proximity to arable land (distance $<$313.2 m) holds particular significance in Pingnan County [37,38]. Cultivated land circumstance created by conscious social labor in the production environment has a significant influence on settlement layout [39]. Roads serve as the medium and channel for internal and external exchanges of rural settlements, which are conducive to the convenience of production and life and the entry of external high-quality production factors, such as the trading of agricultural and sideline products [40,41]. Roads, serving as conduits for internal and external exchanges, enhance production, life convenience, and the flow of production factors, including agricultural and sideline products trading. In the challenging topography of mountainous areas, where transportation is intricate and road density limited, road resources gain added significance. Thus, areas adjacent to roads (distance $<$789.3 m) become the preferred choice for settlement location in Pingnan County. These influencing factors reflect the dual considerations of internal supply and external opening in the selection of rural settlement sites in mountainous areas. Regarding settlements scale, slope, relief degree of land surface and distance to urban centers are the dominant factors of settlement expansion. Gentle terrain (slope $<13.6^{\circ}$, relief degree of land surface $<$6 m) is more suitable for the construction and expansion of settlements, even though the altitude may not be low [42]. In rural areas, the urban centers are central places with regional functions such as market, science, education, culture, health, consumption and public services. The settlements adjacent to urban centers can enjoy the radiation and trickle-down effect of it, and have more development opportunities [43–45]. Therefore, the closer to urban centers (distance to urban centers $<$2519.8 m), the larger the scale of settlements in general. At the present time of industrial upgrading and transformation in Pingnan County, the influence of the commodity market environment that urban centers have on settlements and its economy continues to increase. At the macro level, the commodity market environment affects settlements by improving the ecological environment for production and living, while at the micro level, it is also associated with settlements through the exchange of material and energy. At the same time, there is often a correlation between temperature, precipitation and terrain [46]. Under the combined effects of these natural factors, transportation and location, the scale expansion of settlements is more prominent.

It is worth mentioning that in Pingnan County, although the distance to main rivers is still the primary location for most settlements, its influence is not large. In previous studies, the distance to main rivers was often strongly positively correlated with settlement location or scale [47,48]. It is believed that proximity to rivers favors water extraction for irrigation. There may be two reasons for this different conclusion: one is that the Jiufeng Mountain where Pingnan County is located is distributed with mostly tectonic erosion middle-low mountains, with towering peaks, deep-cut surfaces, deep gullies, and “V"-shaped valleys and rapids. There are few flat places in river valleys, making it difficult to form large-scale settlements [49]. Moreover, the ravines in which the rivers are located are usually channels for floods or mudslides, which can easily lead to geological disasters during heavy rains or extreme weather events, making it difficult for settlements to take shape. Another reason is that in the current era of rapid industrialization and urbanization, settlements are less dependent on rivers [50]. In particular, Pingnan County is not far from more developed coastal cities and is more susceptible to its radiation. Therefore, the correlation between settlement spatial patterns and rivers is not strong.

Compared to plain settlements or other mountainous settlement, the mountainous settlements in metropolitan fringe area possess unique characteristics. On one hand, the natural environment of mountainous areas imposes more robust constraints on settlements than in plain areas. The size of mountainous rural settlements is relatively small due to the limitations of hydrology, weather conditions, land fertility, vegetation and physical geographic processes. In particular, with the increase in climatic extremes, frequent natural disasters have led to the relocation or even disappearance of mountainous settlements [51]. Studies in southwest China and the Loess Plateau reveal a common tendency for the overall spatial pattern of mountainous settlements to be constrained by imposing mountains, shaping a historical spatial pattern that endures today [30]. While contemporary conditions gradually alleviate constraints posed by natural topography, it remains undeniable that these constraints continue to play a foundational role in shaping the unique spatial patterns of mountainous settlements. The localization of rural settlements has always been strongly dependent on natural resource exploitation [52]. On the other hand, when compared to other mountainous settlements, like those in southwest and northwest China, the rural mountainous settlements in metropolitan fringe area experience a more pronounced influence from the social-economic environment. They exhibit a distinct tendency to cluster towards the county seat or central village. Notably, the population from original settlements migrates towards the village center or higher-level, more developed cities, expanding the size of central villages and county seat. This socio-economic influence triggers a dynamic spatial evolution and modern transformation for settlements in metropolitan fringe area. Consequently, their spatial distribution and evolution patterns diverge significantly from those observed in rural settlements in other regions.

In identifying influencing factors, scholars often examine individual factors' superposition with rural settlement spatial locations through buffer zones. While this detailed approach reflects the nuanced relationship between factors and settlement patterns, it lacks a comparative analysis across different factors. In our study, we systematically assessed the strength of different influencing factors before superimposing settlement space and buffer zones. This method is more scientific in revealing the influence of different factors and the pattern of settlement distribution. Moreover, concerning the spatial pattern of settlements, scholars frequently focus on a single attribute, such as location, potentially overlooking other crucial attributes or conflating the meanings of location and scale. In reality, location signifies site selection, revealing the impact of the natural environment and initial human choices, while scale delves into the settlement's development and evolution over time. Our study breaks from this single-attribute paradigm, integrating points reflecting location and patches reflecting scale in a unified manner. By employing binary logistic regression and Geodetector, we identify influencing factors comprehensively, transcending the constraints of previous approaches. This holistic methodology aims to unravel the mechanism by which various influencing factors interact with different attributes of settlements, providing a more comprehensive understanding of their intricate dynamics.

4.2. Implications for rural planning

As mountainous rural settlements of Pingnan County, on the one hand, has the natural characteristics and development laws of the mountainous area itself, and on the other hand, it is also affected by the relatively strong radiation of the coastal areas' socio-economic environment. Based on the current spatial pattern of settlements and the national spatial planning of Pingnan County, combined with field research, optimization of settlements should concentrate on the following: Firstly, settlement land should be allocated rationally and optimally, starting from the spatial pattern of settlements and the dominant driving factors. For a long time, the construction of rural settlements in China has basically been in a state of no planning, no approval, and no management, resulting in scattered, disorderly and unreasonable land use [53]. The government and relevant practitioners should fully consider the interaction of natural conditions, transportation and location in Pingnan County, select areas with low to medium altitude (809–906 m), gentle slopes (slope $<13.6^\circ$, relief degree of land surface <6 m), adjacent to cultivated land, main roads, and urban centers to designate key production and living spaces for settlements.

Secondly, enhancing infrastructure, particularly the development of urban and rural road networks, is imperative. Positioned in metropolitan fringe area, Pingnan County is significantly influenced by road networks and urban centers, crucial factors in settlement location and scale. In current era of industrialization and urbanization, socio-economic factors wield greater influence on settlements than natural factors. Establishing an efficient circulation network for people, materials, and information can promote the flow of resources and the synergistic development of industries among rural settlements and between urban and rural areas. Further, it can reduce the citizenship cost for agricultural transfer populations, alleviates population pressure on coastal cities, and promote the coordinated development of the regional economy and society.

Finally, this study aims to categorize the optimization of settlement spatial layouts in Pingnan County into four types: (1) Urbanization type: rural settlements near the county seat's periphery can undergo transformation into urban settlements. This involves intensifying land resources, boosting infrastructure, and integrating them into the urban planning system. (2) Characteristic development type: settlements with distinctive industries should leverage local resource advantages, enhance infrastructure, and establish symbiotic relationships with developed areas. For instance, settlements focusing on alpine agriculture can progress towards specialized, standardized, and intensified modern agriculture, while those centered around rural cultural tourism should fully exploit historical, cultural, scientific, artistic, economic, and social values, attracting external investment and fostering village regeneration. (3) Limited development type: general village settlements necessitate full utilization of land potential within the settlement, enhancing rural land intensification levels to prevent haphazard expansion and natural resource depletion [54]. (4) Relocation type: high-altitude, steep-slope settlements with challenging transportation can benefit from relocation through town resettlement, central village resettlement, multi-village mergers, or new village construction. This approach acts as a vital catalyst for improving villagers' production and living conditions and broadening their income-generating avenues [55].

5. Conclusions

Scientific understanding of settlements and the promotion of their sustainable development are the general consensus of mankind. Mountainous rural settlements in metropolitan fringe area have their uniqueness which are more vulnerable to urban radiation and face drastic differentiation and reorganization. Unfortunately, these settlements are currently underexplored in academia. This study addresses this gap by scientifically identifying the spatial pattern characteristics and influencing factors of mountainous rural settlements in the metropolitan fringe area. Focusing on Pingnan County in Fujian Province, the research utilizes methods including SDE, ANN, KDE, spatial "hot spot" analysis, binary logistic regression model, and Geodetector. The results show that: (1) The spatial distribution of settlements in Pingnan County is biased toward the southern part of the county; the center of settlement's spatial distribution is located south of the junction of Gufeng Town and Pingcheng Town; the spatial distribution trend of settlements is northeast-southwest. The settlements are generally aggregated, and the aggregation degree of Gufeng Town is obviously lower than that of other towns. (2) The kernel density distribution of settlements presents a "core-periphery" structure dominated by the county seat and a "north-south linear" structure dominated by the layout of Jiufeng Mountains; the spatial pattern characteristics show high-density, large patches in Gufeng Town, high-density, small patches in Changqiao Town, Tangkou Town and Gantang Town, and medium-density or low-density, small patches in the rest of the town. (3) Settlement location in Pingnan County is mainly affected by the elevation, distance to cultivated land, and distance to main roads, while settlement scale is mainly affected by slope, relief degree of land surface, and distance to urban centers. Nevertheless, the influence of slope aspect and distance to main rivers is weak. The interaction between factors all have enhancement effects, and the enhancement effect formed by natural terrain and location conditions is the most prominent. These features underscore the unique constraints faced by mountainous rural settlements in metropolitan fringe area — distinct from plains due to natural topography and diverging from general mountainous settlements like those in southwest and northwest China due to pronounced socio-economic influences. Based on these results, it is believed that settlement land should be allocated rationally and optimally, based on the spatial pattern of settlements and the dominant influencing factors; improve the infrastructure of settlements, especially the construction of urban and rural road networks; settlements can be classified into four categories, namely, urbanization type, characteristic development type, limited development type and relocation type, to promote the optimization of land resources and rural revitalization.

Although this study has revealed the spatial pattern characteristics and influencing factors of settlements in Pingnan County, it still has limitations. On the one hand, for the selection of influencing factors, due to the availability of data, there are fewer indicators selected for socio-economic aspects, such as the GDP, the proportion of primary, secondary and tertiary industries of individual settlement. The collection method of relevant indicators can be expanded in the future. On the other hand, given the dynamic nature of settlements and the study's reliance on data from a single period for exploring spatial patterns in Pingnan County, conclusions regarding their evolution over the past decade, and the predominant influencing factors in this process, remain elusive. Acknowledging this limitation, future research will encompass data from multiple periods to provide a comprehensive understanding of the long-term evolution of settlement spatial patterns and the enduring impact of influencing factors.

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Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Song Chen: Writing - review & editing, Writing - original draft, Methodology, Formal analysis, Conceptualization. **Xiyue Wang:** Writing – review & editing, Validation, Funding acquisition, Conceptualization. **Qing Lin:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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