

Spatial Evolution Characteristics and Pattern Optimization of Rural Settlements in the Central Henan Region

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Abstract

With the deepening of new-type urbanization, the spatial evolution of traditional rural settlements in China has intensified and faces reconstruction. This study investigates the spatial evolution characteristics of rural settlements in the central Henan region, aiming to enrich the geographic information system of the rural settlement spatial pattern and provide theoretical and practical references for the development and transformation of rural settlements in Henan. Using kernel density estimation and GIS spatial analysis methods, with 2000, 2010, and 2020 as time nodes, this study calculates and analyzes the population density of rural settlements to characterize their spatial scale. Comparative analysis is employed to determine the spatial evolution characteristics of rural settlements in the central Henan region over the past 20 years. The results indicate that: (1) From 2000 to 2020, the density of rural settlement distribution in the central Henan region generally showed a decreasing trend, following the pattern of "declining from north and south towards the center," with a decrease in density first observed in the southern and northern regions, followed by a decline in the central region; (2) The distribution characteristics of settlements have shifted from being distributed across the entire region to becoming concentrated, ultimately focusing in the central region, specifically Xuchang City and Pingdingshan City. The spatial pattern of rural settlements in the central Henan region still faces issues such as high settlement density, uneven development with a focus on the southern and northern regions while neglecting the central region, and a lengthy evolution cycle. To address these issues, the following optimization strategies are proposed: optimize the spatial pattern of rural settlements in central Henan, upgrade settlement density; strengthen development in the central region; prioritize the construction of small towns to promote local urbanization.

Keywords

Rural Settlements; Spatial Evolution; Optimization; Kernel Density Estimation; Central Henan Region.

1. Introduction

With the acceleration of the socialist process and the deepening of new-type urbanization, the spatial evolution of traditional rural settlements in China has intensified and faces reconstruction, exhibiting new characteristics at different stages. The spatial evolution of rural settlements is influenced by natural, social, and cultural factors, with cultural and social influences being predominant [1]. Settlements, as the habitation areas of rural populations, are meaningful as they accommodate population activities. As urbanization progresses, rural populations continuously migrate to towns, leading to a decrease in the cultural significance of rural settlements, a weakening or even disappearance of their population-bearing function, and eventually resulting in the "hollowing out" of rural settlements, which face abandonment, consolidation, or elimination, evolving into a new stage of rural settlement spatial pattern.

Social factors influencing the spatial evolution of rural settlements include policy measures such as elimination, consolidation, or expansion implemented in response to social development needs. Studying the spatial evolution characteristics of rural settlements is crucial for understanding the process and characteristics of rural settlement spatial pattern changes, as well as enriching the geographic information of rural settlement spatial patterns.

In recent years, research on rural settlements has garnered widespread attention from scholars, focusing mainly on distribution patterns, spatial evolution, and pattern optimization. Research has primarily concentrated on administrative regions such as provinces [2-3], provincial municipalities [4], municipal districts [5], and counties [6-7], or specific forms such as mountainous areas [8], river basins [9], and hilly regions [10]. For example, Song Xiaoying et al. [7] used kernel density estimation to find that the spatial pattern evolution of rural settlements in Yuxian from the Shang and Zhou dynasties to the Qing dynasty exhibited a shift from concentrated to random distribution. Min Jie et al. [5] studied the spatial evolution characteristics of rural settlements in the Three Gorges Reservoir area before (1995) and after (2012) the reservoir's filling, identifying "eastward increase, westward slow down, and central decrease" as a significant spatial differentiation feature. Gao Danyang et al. [9] concluded that the spatial scale structure of rural settlements in the Fenhe River basin tends toward centralization using GIS spatial analysis methods. Xiao Luyao [11] found that the RROD model is an ideal model for optimizing the spatial arrangement of rural settlements in Changning City with a focus on quality of life. Wang Fang [12] summarized that the core-led and cluster-radiated (core-periphery) and network-interwoven, coordinated development (network) models are the target optimization patterns for traditional village-town spatial planning in Yuantan Town, Qianshan County, Anhui Province. Research on rural settlements in the central Henan region is still in its early stages, with limited theoretical and empirical results available. This paper uses this region as a case study, employing kernel density estimation and GIS spatial analysis methods to explore and analyze the spatial evolution characteristics of its rural settlements and proposes optimization strategies. This research provides theoretical references and practical insights for rural development and transformation in Guangxi, and significantly enriches the geographic information system of rural settlement spatial patterns.

2. Study Area Overview and Data Sources

2.1. Study Area

Henan Province, abbreviated as "Yu," is located in the central and eastern part of China, in the southern part of the North China Plain along the middle and lower reaches of the Yellow River. Its geographical coordinates range from 31°23'N to 36°22'N latitude and from 110°21'E to 116°39'E longitude. The province is divided into five regions: Eastern Henan, Western Henan, Southern Henan, Northern Henan, and Central Henan. Central Henan hosts 19% of Henan's rural population, covering four prefecture-level cities and 33 counties (cities, districts), with a resident population of approximately 24.36 million and a population density of 1055 people per km². The region has over 7,627 administrative villages, and its urbanization level is continually rising, leading to ongoing changes and reconstruction of rural settlements during the urbanization process.

2.2. Data

The data for this study are sourced from the "Henan Statistical Yearbook (2001–2021)" and the "National Economic and Social Development Statistical Bulletins (2000–2020)" for Zhengzhou, Pingdingshan, Xuchang, and Luohe Cities.

3. Research Methods

The principle of kernel density estimation effectively represents settlement spatial patterns and provides a good approach for comparative analysis of historical settlement evolution at different stages. It is a widely used method in the study of rural settlement evolution. Therefore, this study employs kernel density estimation and GIS spatial analysis methods, using 2000, 2010, and 2020 as time nodes to calculate and analyze the population density of rural settlements, which characterizes their spatial scale. By comparative analysis, the spatial evolution characteristics of rural settlements in the central Henan region over the past 20 years are determined, and optimization strategies are proposed based on these findings. Kernel density estimation effectively addresses the limitations of parameter estimation by studying data distribution characteristics from the data samples themselves. It is used in probability theory to estimate unknown density functions and is highly valued in statistical theory and application.

Let P represent any point in space, and $p_1, p_2, p_3, \dots, p_n$ represent the attribute data of n sample points. The characteristics of the samples can be reflected through the kernel density function. The kernel density calculation formula is as follows:

The formula for kernel density estimation is shown in Equation (1), where k represents the kernel and h denotes the bandwidth. A smaller bandwidth results in a smaller bias in the kernel density estimate. The optimal bandwidth can be determined using the Asymptotic Mean Integrated Square Error (AMISE), which is used to find the minimum value of $AMISE(h)$ and calculate the optimal bandwidth h . The kernel function is used to calculate the kernel density, where H represents distance. Substituting the above into the kernel density estimation formula yields the kernel density, where H_j is the distance between point p and the observed point p_i .

$$f(p) = \frac{1}{nh_j} \sum_{i=1}^n k\left(\frac{p_i - p}{h}\right) \quad (1)$$

In the formula, k represents the kernel, h denotes the bandwidth, and $(p_i - p)$ indicates the distance between point p and the observed point p_i . A larger bandwidth h reflects the overall distribution characteristics of sample points in the study area, while a smaller bandwidth highlights the local distribution characteristics. Additionally, within the same study area, the bandwidth can be either fixed or vary based on the number and density of sample points. The choice of bandwidth value is based on the range of the study area and the average distance between sample points. To better represent the changes in the distribution characteristics of rural settlements over different periods, this study uses a fixed bandwidth value.

4. Spatial Evolution Characteristics of Rural Settlements in Central Henan

4.1. Current Characteristics of Settlements

The research results show (Table 1) that by 2020, the number of administrative villages in Central Henan reached 7,627, accounting for 17% of the total number of administrative villages in Henan Province. Among them, Pingdingshan City has the highest number of administrative villages, representing 33.3%. The rural population in Central Henan is 8.1482 million, making up 33.4% of the region's permanent population and 19% of Henan's total rural population. Within Central Henan, Zhengzhou City has the highest proportion of the rural population, at 33.4%. Central Henan covers an area of 23,100 km², with 13.8% of this land area supporting 16.9% of Henan's administrative villages and 19% of the province's rural population.

Table 1. Comparison of Administrative Village Numbers in Henan Province, Central Henan, and Subordinate Cities in 2020

	Number (Units)				Population (10,000)		Area (10,000 km ²)
	City	County (District)	Town (Township)	Administrative Village	Permanent Population	Rural Population	
Henan Province	39	136	1791	45148	9941.00	4304.00	16.70
Central Henan	13	24	294	7627	2436.00	814.82	2.31
Zhengzhou City	6	7	86	2211	1262.00	272.15	0.76
Pingdingshan City	3	8	86	2547	499.00	232.30	0.79
Xuchang City	3	4	76	1600	438.00	203.46	0.50
Luohe City	1	5	46	1269	237.00	106.91	0.26

Comparing the changes in the number of townships and administrative villages from 2000 to 2020 in Henan Province, Central Henan, and its subordinate cities (Table 2), over the 21-year period, the number of townships in Henan Province decreased from 2,129 in 2000 to 1,791 in 2020, an average annual decrease of 16. The number of administrative villages decreased from 48,206 in 2000 to 45,148 in 2021, an average annual decrease of 146. In Central Henan, the number of townships decreased from 350 in 2000 to 294 in 2021, and the number of administrative villages decreased by 878, with an average annual decrease of 42. Additionally, the number of townships and administrative villages in Zhengzhou, Pingdingshan, Xuchang, and Luohe Cities also changed annually. This indicates that from 2000 to 2020, with ongoing social development and deepening urbanization, the number of rural settlements in Central Henan has continuously changed.

Table 2. Changes in the Number of Townships and Administrative Villages in Henan Province, Central Henan, and Subordinate Cities (2000-2020)

	2000		2010		2020	
	Town (Township)	Administrative Village	Town (Township)	Administrative Village	Town (Township)	Administrative Village
Henan Province	2129	48206	1878	47311	1791	45148
Central Henan	350	8505	309	8238	294	7627
Zhengzhou City	118	2316	92	2284	86	2211
Pingdingshan City	99	2609	91	2582	86	2547
Xuchang City	82	2333	78	2132	76	1600
Luohe City	51	1247	48	1240	46	1269

4.2. Settlement Evolution Characteristics

The continuous changes in quantity are inevitably accompanied by ongoing spatial pattern evolution. To provide a clearer view of the rural settlement evolution process in Central Henan from 2000 to 2020, this study uses the years 2000, 2010, and 2020 as time nodes. It overlays the rural settlement population scales for each year onto the spatial data of each county. By employing kernel density estimation, the spatial visualization of rural settlement scales across different periods is achieved. The spatial evolution results of rural settlements in Central Henan are shown in Figure 1.

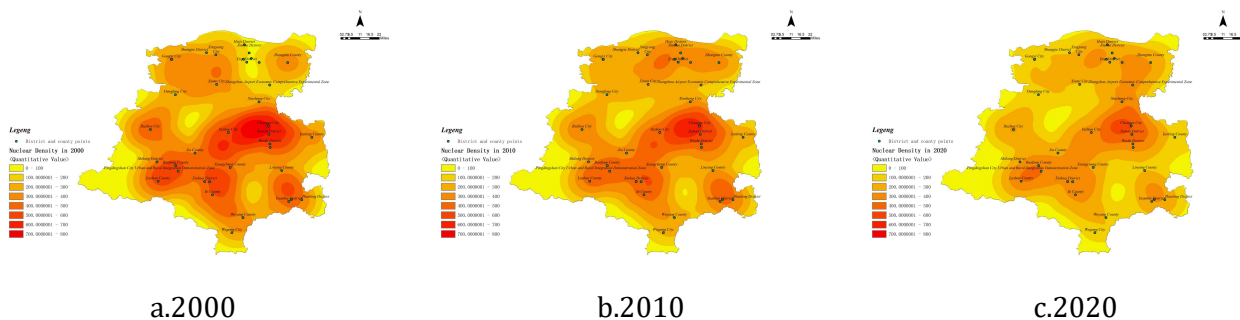


Figure 1. Spatial Evolution of Rural Settlement Patterns in Central Henan (2000-2020)

As shown in Figure 1, from 2000 to 2020, the distribution density of rural settlements in Central Henan overall decreased, following a pattern of "decline from north and south towards the center." Specifically, the density in the southern and northern regions decreased first, followed by a decline in the central region. The distribution characteristics of settlements shifted from a broad regional scale to a concentrated distribution, ultimately focusing in the central area, specifically in Xuchang City and Pingdingshan City. This indicates that, over 20 years of social development and urbanization in Central Henan, rural development has made substantial progress. The result is a direct decrease in rural settlement density in the northern and southern regions, while some counties (districts) in the central region achieved a one-level decrease. Additionally, despite the decrease in settlement density in the northern and southern regions, the density in the central region did not increase. This suggests that the overall number of rural settlements in Central Henan is in a continuous decline trend. Since population movement is a fundamental reason for changes in rural settlements, it indicates that from 2000 to 2020, rural populations continuously moved to towns, reflecting significant achievements in urbanization in Central Henan. The settlement density remains high in Xuchang City and Pingdingshan City, showing little change over the 21 years. These areas are key regions for future urbanization, particularly in Pingdingshan's Luxian County, Baofeng County, and the Pingdingshan Urban-Rural Integration Demonstration Zone; as well as in Xuchang City's Changge City, Jian'an District, and Weidu District, with Changge City maintaining a high density throughout 2000-2020.

5. Optimization of the Spatial Pattern of Rural Settlements in Central Henan

5.1. Existing Issues

(1) High Settlement Density. According to the results of the spatial pattern evolution of rural settlements in Central Henan (Figure 1), as of 2020, most of the rural settlement densities in the region were still at the second level (100–200), with the remaining counties (districts) having high-density levels. This indicates that despite 21 years of spatial pattern evolution

showing significant development in rural areas, the settlement density remains high, leaving considerable room for improvement.

(2) Uneven Rural Development. Since 2000, the rural settlement density in Central Henan has shown a pattern of "higher in the central region, lower in the north and south" (Figure 1a). Over the 21 years from 2000 to 2020, the rural settlement density in the central and southern regions has shown a declining trend, with a more pronounced decrease in the northern region (Figures 1a and 1c). This indirectly suggests that rural development in the northern region has progressed faster than in the central region, and over time, the northern and southern regions have exerted a certain radiative and driving effect on the central region. This characteristic of rural development in Central Henan is closely related to local government policy support and guidance.

(3) Long Evolution Cycle. According to the results in Figures 1a and 1b, the spatial evolution of rural settlements in Central Henan from 2000 to 2010 did not show significant characteristics, with little change in distribution patterns. By 2020 (Figure 1c), rural settlements began to exhibit certain spatial pattern differentiation features, indicating that rural settlement evolution in Central Henan requires a 20-year period to show notable pattern changes.

5.2. Optimization Suggestions

(1) Density Upgrade. Based on the results of this study, it is evident that the spatial pattern of rural settlements in Central Henan still suffers from high settlement density. There is a need to "upgrade" the settlement density, meaning to elevate the current density to a higher level. The reduction in rural settlements reflects improvements in rural living standards and accelerated urbanization. Thus, two approaches can be taken: First, enhance rural prosperity by accelerating agricultural transformation. It has been proven that traditional agriculture, while meeting basic needs, does not significantly improve rural wealth. Therefore, transitioning to high-efficiency agriculture and increasing agricultural output is crucial. Additionally, increasing the share of secondary and tertiary industries in rural areas is key to upgrading settlement density, as these industries play a significant role in attracting rural employment and providing additional income sources. Second, promote the new urbanization process by implementing policies that attract rural populations to migrate to urban areas, lowering the urbanization thresholds, and introducing household registration policies to facilitate rural-to-urban migration.

(2) Strengthen Central Region Construction. The study indicates that while the overall rural settlement density in Central Henan decreased from 2000 to 2020, the central region has consistently maintained high-density distribution with little change. The central region has long been the slowest in rural development in Central Henan. Therefore, strengthening new rural construction and leading new urbanization should receive significant government attention. Increased efforts and financial support should be allocated to this region. Given the underdevelopment in agriculture and the lack of distinctive local brands, the government could use this region as a pilot for new rural construction reforms, prioritize the introduction of secondary and tertiary industries, and assign government personnel for targeted guidance and close monitoring of industry development. Establishing local agricultural or industrial brands could boost economic development. Improving economic conditions is crucial for advancing local rural areas.

(3) Prioritize the Construction of Small Towns and Promote Local Urbanization. Large towns, due to their long-standing existence, have developed systems that are now approaching saturation with limited carrying capacity. Rural areas, with large populations and land areas but relatively underdeveloped economies, benefit from establishing small towns within existing rural regions. This approach efficiently utilizes rural land and facilitates local migration. Therefore, selecting small towns with convenient transportation, favorable surrounding

resources, a solid industrial base, and relatively advanced economies as destinations for guiding rural residents can be an effective strategy. The government should provide financial support, enhance infrastructure in small towns, improve service levels, and introduce policies to promote local urbanization.

6. Conclusion

This study employed kernel density estimation and GIS spatial analysis methods, using 2000, 2010, and 2020 as time nodes to calculate and analyze rural settlement population density, thereby determining the spatial evolution characteristics of rural settlements in Central Henan over the past 20 years. The results indicate that from 2000 to 2020, the density of rural settlements in Central Henan generally decreased, following a "north-south to central" pattern, with the distribution shifting from large-scale coverage across the region to concentrated distribution, ultimately focusing in the central area. However, the spatial pattern of rural settlements in Central Henan still faces issues of high settlement density, uneven development ("heavy in the north and south, light in the central"), and long evolution cycles. Therefore, strategies such as optimizing the spatial pattern of rural settlements, upgrading density, strengthening construction in the central region, prioritizing the development of small towns, and promoting local urbanization are crucial for guiding the development and transformation of rural settlements in Central Henan.

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