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Spatiotemporal dynamics of rural settlement evolution in Guangdong Province, China

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This study analyzes the spatiotemporal dynamics of rural settlement evolution in Guangdong Province, China, examining their transformation amid rapid urbanization and industrialization over the past 20 years. Rural settlements serve as primary spatial carriers for production and living activities, embodying multiple functions including production, living, ecological, and cultural aspects. Using GIS-based analytical tools, including landscape pattern indices, average nearest neighbor index, kernel density estimation, and geographical detector methods, we examined settlement evolution patterns and their driving factors. Results show a continuous decline in settlement numbers, while patch areas exhibited a U-shaped trend of decreasing then increasing. Settlement patterns shifted from "reduction" to "integration", with intensifying spatial agglomeration over time. The Pearl River Delta and Eastern Guangdong regions followed similar trajectories, reflecting the impact of urbanization and industrialization on rural development. Multiple factors, including natural conditions, socioeconomic variables, and locational accessibility, drove these changes. The spatial distribution of rural settlements demonstrates an overall trend of agglomeration, which has gradually intensified over time, leading to significant variations in settlement density across different regions. The findings reveal significant regional disparities and temporal changes in settlement patterns, highlighting the complex interplay between rural transformation and urban development. This research contributes to understanding rural transformation processes in developing countries and emphasizes the need for differentiated approaches in spatial planning and rural revitalization strategies to address the challenges of disordered land expansion and population hollowing while promoting sustainable rural development.

Keywords Rural settlement, Spatiotemporal dynamics, Driving factor, Urbanization, China

The adaptive transformation of rural areas within the frameworks of urbanization, industrialization, and globalization is emerging as a novel perspective in rural development research. The elements of people, land, economy, and space in rural settings are gaining significant attention[1]. Rural settlements, serving as the primary spatial carriers for the production and living activities of rural residents, embody various functions—production, living, ecological, and cultural—and are central to the relationship between people and land[2]. As rapid urbanization, industrialization, and globalization proceed, the development pattern between urban and rural areas is transforming swiftly. Migration from urban to rural areas driven by policy initiatives, along with emerging rural industries such as e-commerce and rural tourism, reshapes the rural spatial system characterized by "physical, social, and cultural" dimensions. Meanwhile, rural settlements are confronting prominent issues, including disordered land expansion, fragmented land use, and population hollowing, leading to vulnerabilities and instability in their development courses[3–5]. Therefore, exploring the self-development capabilities of rural areas and restructuring the spatial layout of residential sites is an essential path for the further development of rural regions.

The spatial distribution of rural settlements has long been a central focus of scholarly inquiry. Research on rural settlements began in the nineteenth century and mainly limited to small regional studies, with early explorations of their causes, types, functions, and planning primarily relying on qualitative descriptions[6]. During this period, Christaller developed the central place theory, guiding spatial planning in towns[7].

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Following the 1980s, influenced by various philosophical trends, studies on rural settlements shifted towards a multidimensional, interdisciplinary approach, examining spatial distribution, types, and systems. Research content transitioned from a focus on material aspects to social and cultural dimensions[8,9]. For instance, the study of rural settlements increasingly incorporated findings from behavioral sciences, emphasizing the impact of human decision-making on the distribution, morphology, and structure of settlements[10,11]. Harvey radically argued that settlement studies should consider social institutions, political power, and economic environments[12]. Simultaneously, the acceleration of urbanization and the industrialization of rural areas have fundamentally altered the structure of rural settlements[13,14], becoming significant topics within rural settlement research. Since the twenty-first century, research on rural settlements has tended toward interdisciplinary integration, focusing on new issues and changes, including the relationship between population density, economic development, and rural settlements[15–17], the visualization of rural landscapes[18], and the reconstruction of rural settlements amid socioeconomic changes[19]. Furthermore, the use of advanced techniques like multi-temporal satellite data analysis combined with machine learning is increasingly recognized for its potential in spatial studies. This approach can significantly improve the analysis and presentation of complex datasets related to both urban and rural environments[20].

The factors influencing the formation, distribution, and development of rural settlements have evolved from single to multiple dimensions, transitioning from focusing on natural factors to a comprehensive consideration of social, economic, and natural factors. Compared to urban settlements, rural settlements, deeply rooted in agriculture and natural resource development, are closer to nature and more susceptible to geographical influences. Topography and rivers are primary factors affecting the spatial layout of settlements[21]. While elevation, slope, and aspect have minimal effects on the spatial distribution of settlement patterns in plains, they are dominant factors in mountainous areas[22]. The state of land resources and types of land use directly influence the spatial distribution of rural settlements[23]. The factors affecting the spatial layout of rural settlements have gradually expanded into the socio-cultural realm. The socioeconomic environment plays a decisive role in the dynamic migration of spatial patterns in rural settlements[24]. The impacts of policies, demographics, culture, technology, and the push-pull effects of urbanization on settlement layouts have become increasingly significant[25,26]. It is argued that urbanization creates networks of villages and towns, with the accessibility of transportation and information between these networks serving as a primary driver of rural landscape evolution[27]. Scholars have identified two key factors driving changes in rural settlements: adjustments in rural industrial structures and fluctuations in the agricultural population[28]. In China, policies such as economic reform, rural revitalization, and land tenure reforms have fundamentally altered the system of rural settlements[29]. The evolution of rural settlement layouts is a process influenced by a combination of natural resource conditions, locational accessibility, and socioeconomic levels. Recent studies in India provide detailed insights into these complex relationships. Spatial regression models have highlighted the influence of rurality, female literacy rates, and caste systems on household wealth distribution across numerous districts[30]. Additionally, many districts have been shown to perform poorly in sustainable livelihood, with large regional variations in economic and social domains[31]. Spatial variations across urban centers have also been assessed using GIS and composite indices, achieving a high explanatory power in their models[32]. The impact of mountainous terrain on settlement distribution has been demonstrated, as well[33]. Furthermore, the relationship between rural settlement distribution and infrastructure allocation has been analyzed from the perspective of healthcare service accessibility[34]. These studies collectively emphasize the importance of considering diverse socioeconomic and environmental factors when analyzing rural settlement patterns. In Eastern Europe, researchers discovered that rural settlements displayed a "this for that" change characteristic as society developed[35]. It is also found that rural settlements in the United States continued to grow and the rural settlements surrounding large cities exhibit a layered structural characteristic[36,37]. Some scholars proposed a "four-wheel drive" mechanism for settlement spatial evolution, highlighting the interplay of economic development, urbanization, transportation networks, and institutional management as key factors driving the evolution of urban-rural settlement systems[38].

The advancement of spatial analysis theories and intelligent technologies has propelled the development of various spatial quantification research ideas and methods. Scholars commonly employ GIS-based techniques to study the evolution of rural settlements[39] and have begun integrating fuzzy mathematics with neural networks to explore regional distribution patterns[40,41]. While extensive research exists on rural transformations in developed regions, studies on rural settlement evolution in developing countries like China have often overlooked the critical role of urbanization policies and locational accessibility in shaping settlement patterns. Previous research has highlighted the multifaceted functions of rural settlements but has not fully examined how state-led urbanization policies and varying degrees of accessibility to urban centers influence settlement evolution. Furthermore, while some studies address the socio-economic restructuring of rural areas, they rarely analyze how these changes interact with spatial transformation across different development stages. This theoretical and policy gap is particularly evident in the context of rapidly urbanizing regions experiencing dramatic socio-economic transitions. To address these limitations, this study employs GIS-based analytical tools and geographical detector methods to examine the spatiotemporal dynamics of rural settlement evolution in Guangdong, focusing specifically on how urbanization policies, accessibility factors, and socio-economic restructuring jointly shape settlement patterns. By analyzing a region characterized by stark regional disparities and rapid development, this research contributes to both theoretical understanding of rural settlement evolution in developing contexts and practical policy-making for rural revitalization. The findings reveal how varying combinations of policy interventions, accessibility conditions, and socio-economic factors produce distinct regional and temporal variations in rural settlement patterns, offering insights for creating more targeted and effective rural development strategies.

This paper follows a structured approach of "spatial patterns—evolution processes—evolution mechanisms—pattern optimization," aiming to analyze spatial and temporal changes in rural settlements in Guangdong over

the last 20 years. It will investigate the mechanisms driving these changes and explore optimization strategies for rural settlement spaces in developing countries with varied evolutionary paths. This research addresses significant gaps in the long-term dynamic monitoring of rural settlements, delineating general rules of spatial evolution at different development stages, predicting future trends, and identifying sustainable development pathways for rural communities. By focusing on Guangdong, characterized by stark regional disparities—where the affluent Pearl River Delta contrasts with less developed mountainous areas that make up over 70% of the province's territory but contribute less than 20% to its GDP—this research examines how developments unfold and transform within varying socioeconomic environments. Additionally, it examines rural population trends in urbanized areas, highlighting how rapid urbanization influences surrounding regions, with rural residents increasingly engaging in non-agricultural occupations. This research encompasses both meso and micro scales, providing a multifaceted perspective on rural settlement development. It investigates the evolutionary patterns of rural settlements across different developmental stages and scales, ultimately proposing policy recommendations that contribute to sustainable rural development and spatial planning strategies at the village and township levels. To address these research questions, we employed a combination of GIS-based analytical tools and geographical detector methods to investigate the spatiotemporal dynamics of rural settlement evolution in Guangdong Province. The following sections detail the methodology, results, discussions and implications of our study.

Methods

To analyze the spatiotemporal dynamics of rural settlement evolution in Guangdong Province, we adopted a structured approach combining landscape pattern indices, kernel density estimation, average nearest neighbor analysis and geographical detector. The analytical framework and data sources are also detailed below.

Theoretical framework

The evolution of rural spatial studies has progressed from "productivism" through "post-productivism" to "multifunctionalism."[42,43] Previous research on spatial production has posited that rural transformation transcends mere alterations in architectural forms and landscape environments, encompassing fundamental modifications in residents' quotidian practices[44]. The theoretical foundation established that "space" is not simply a passive container external to production relations but rather a product of intentional social activities[45]. The spatial triad dialectic framework shown in Fig. 1 comprises three interconnected dimensions: spatial practice (perceived physical environment), representations of space (abstract and conceptual space shaped by ideological constructs, power relations, and knowledge systems), and representational space (lived space emerging from everyday life within specific material contexts, reflecting the social attributes of space). These three dimensions are intrinsically interconnected, mutually constitutive, and collectively contribute to spatial production and transformation. The theory of spatial production emphasizes that physical spatial transformations are manifestations of complex social processes, thereby providing a theoretical foundation for analyzing the
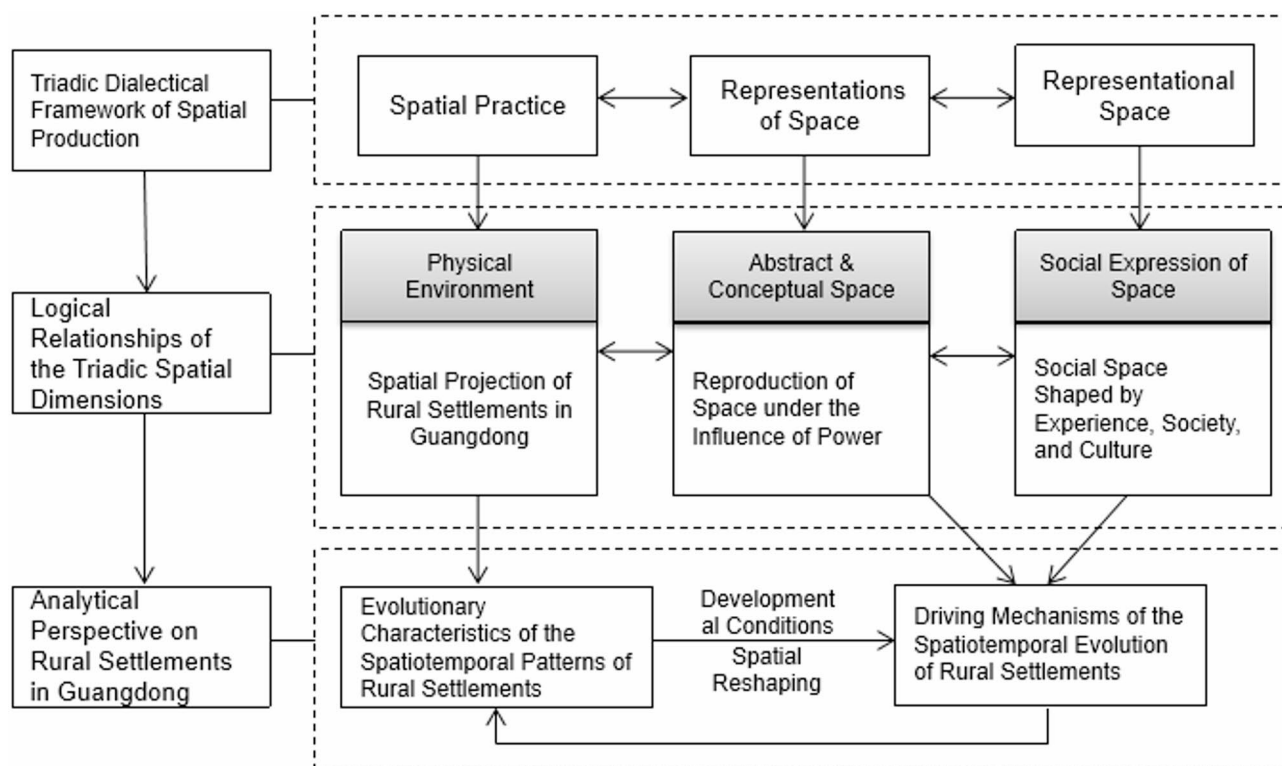

Fig. 1. Theoretical framework of spatiotemporal evolution of rural settlements.

evolution of rural settlements. This paper employs the spatial triad as an analytical framework to examine the transformation of rural settlements in Guangdong province.

Study area

The selected Guangdong case in this study is highly representative due to its status as China's leading economic province, coupled with significant regional development disparities within its borders. Located in the southernmost part of mainland China, Guangdong lies between latitudes 20°09′ to 25°31′ N and longitudes 109°45′ to 117°20′ E (see Fig. 2). The province's topography is generally low-lying, with higher elevations in the north and lower elevations in the south. The northern region is dominated by mountains and high hills, while the southern region is primarily composed of plains and plateaus. Mountains and hills account for approximately 60% of Guangdong's total land area. Administratively, the province is divided into 21 prefecture-level cities, which are categorized into the Pearl River Delta, Eastern Guangdong, Western Guangdong, and Northern Guangdong regions. According to the 2021 National Land Change Survey Statistics, Guangdong covers an area of 179,800 square kilometers, representing 1.9% of China's total land area.

Guangdong Province boasts a developed economy, with a GDP value of 13,567.316 billion yuan in 2023, making it the first province in the country to surpass 13 trillion yuan. It has maintained the highest economic output in the country for 35 consecutive years. Generally, Guangdong is divided into four major regions: the Pearl River Delta, Eastern Guangdong, Western Guangdong, and Northern Guangdong. The issue of regional disparity has become increasingly pronounced, forming a pattern of diminishing regional differences from the Pearl River Delta to the eastern and northern regions of Guangdong[46]. Between 1994 and 2016, the trajectory of regional economic disparity in Guangdong exhibited a notable inverted "U" shape, with the gap beginning to widen again from 2016 onwards[47]. In recent years, the combined area of the eastern and northwestern regions of Guangdong has exceeded 70%, yet their contribution to GDP is less than 20%.

Therefore, selecting Guangdong Province as a typical case can reveal the evolutionary patterns and influencing factors of rural settlements across different stages of development, providing strong representativeness. The research findings will provide scientific evidence for a deeper understanding of the inherent rules of rural development and enrich the content of rural settlement studies.

Data sources

This study utilizes land use data sourced from the China Multi-Period Land Use/Land Cover Remote Sensing Monitoring Database, specifically the land use change survey data for Guangdong Province from the years 2002, 2012, and 2022. The remote sensing imagery is obtained from the Shenzhen Municipal Planning and Natural Resources Bureau, as well as the Urban Renewal and Land Consolidation Bureau of Shenzhen's Dapeng New District, with a relatively ideal resolution of 30 m × 30 m.

Digital Elevation Model (DEM) data is sourced from the Geospatial Data Cloud website (http://www.gscloud.cn), providing elevation and slope data. Data regarding rural settlements, temperature, precipitation, GDP, and population spatial distribution is obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn). Nighttime light remote sensing data is derived from the Luojia1-01 Dataset (http://59.175.109.173:8888/index.html), which has been calibrated using ENVI software. Road network data is sourced from the National Geographic Information Resource Catalog Service System (https://www.web-map.cn). During data processing, the rural settlement patch boundaries from the Third National Land Survey of Guangdong Province were used to calculate the land area for each administrative village (township) within 111 administrative units from 2002 to 2022. To avoid the impact of administrative boundary adjustments, this study uniformly adopts these administrative village boundaries for settlement scale statistics, ensuring that the boundaries of towns and villages remain consistent throughout the study period, thereby guaranteeing the comparability of settlement scales during the research timeframe. Socioeconomic data for Guangdong Province is compiled from various relevant statistical materials, including the Guangdong Statistical
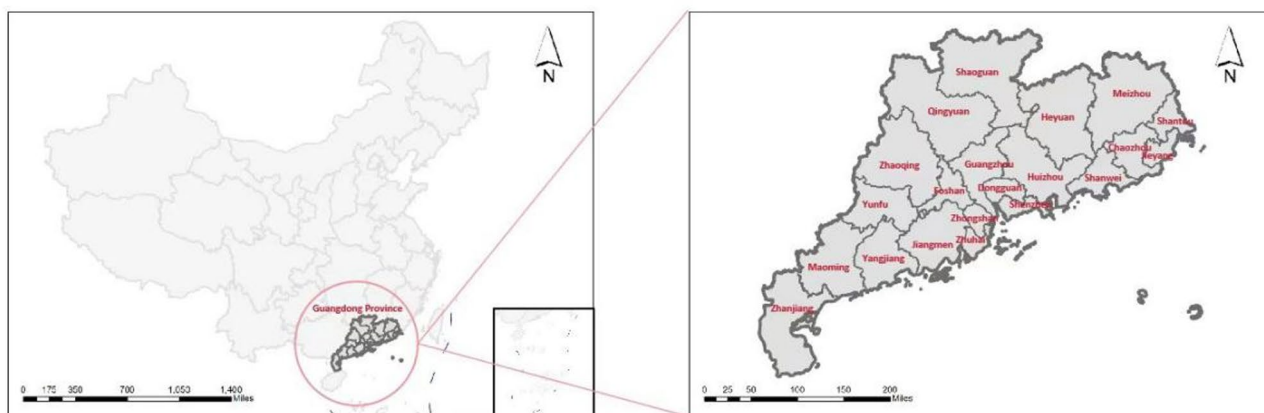

Fig. 2. Location of the study area.

Yearbook (2012–2022), the Statistical Bulletins on National Economic and Social Development of Guangdong and Its Municipalities (2012–2022), and the Guangdong Rural Statistical Yearbook (2012–2022).

Analytical tools

Spatial landscape pattern analysis

The landscape pattern index serves as a quantitative metric that reflects the structure of rural settlement patches and their spatial configuration characteristics. Compared to conventional spatial pattern analysis methods, the landscape pattern index analysis can effectively and objectively indicate the types, shapes, sizes, numbers, spatial combinations, changes in landscape patterns, and trends in land use evolution of landscape patches. Drawing on existing research, this study selects indicators such as Total Area (TA), Number of Patches (NP), and Mean Patch Size (MPS), utilizing the landscape analysis software Fragstats 4.2 to analyze the evolution patterns of the scale and spatial structure of rural settlements in Guangdong Province over three distinct periods.

Kernel density estimation (KDE)

KDE is a non-parametric method for calculating surface density that infers the overall distribution characteristics based on sample data. This method has seen mature applications in the spatial distribution patterns and change characteristics of various land use types. In this study, ArcGIS 10.5 software is employed, utilizing a grid data size of 1000 × 1000 and a bandwidth of 2 km to create a density distribution map of rural settlements. This analysis aims to elucidate the spatial distribution density characteristics of rural settlements in Guangdong Province. The estimation model is defined as follows:

$$f_n = \frac{1}{nh} \sum_{i=1}^{n} k\left(\frac{x - x_i}{h}\right)$$

In the equation, f_n represents the estimated kernel density value for the spatial distribution of rural settlements; n denotes the number of rural settlement patches, h is the bandwidth, k is the kernel density function, and $x - x_i$ signifies the distance from the rural settlement plot x to the sample settlement x_i. A larger f_n value indicates a higher density of rural settlement distribution.

Average nearest neighbor analysis (ANN)

The ANN analysis reveals the spatial distribution pattern of specific features by comparing the actual nearest distances between point features with the theoretical nearest distances in a random model. This method allows for a quantitative analysis of the changes in spatial clustering of rural settlements in Guangdong Province. The ANN statistic R is derived from the average of the nearest distances observed compared to the expected average under a random distribution, which is calculated through the following process[48]:

1. Calculate the distance from each point to its nearest neighboring point (d_{min}).
2. Compute the mean distance $\left(\overline{d}_{min}\right)$ based on the total number of points (n) in the study area.
3. In a random distribution pattern, the expected ANN distance $E\left(\overline{d}_{min}\right)$ is calculated, which is dependent on both the study area (A) and the number of rural settlements (n).

$$E\left(\overline{d}_{min}\right) = \frac{1}{2\sqrt{n/A}}$$

4. The nearest neighbor index (R) is then determined by: $R = \frac{\overline{d}_{min}}{E\left(\overline{d}_{min}\right)}$

The value of R ranges from [0, 2.149]. If R > 1, it indicates that rural settlements in Guangdong are dispersed. If R < 1, it suggests that the spatial distribution of rural settlements is relatively concentrated. Furthermore, the Z value can be calculated to measure the difference between the observed and expected values relative to the standard error of the average nearest distance, providing insight into the degree of clustering or dispersion between the observed pattern and the random model.

Geographical detector (GD)

The Geographical Detector (GD), proposed by researcher Wang Jinfeng from the Chinese Academy of Sciences, effectively identifies the influence of various factors on the spatial distribution of geographical features and explores the driving forces behind spatial differentiation. The core idea is that if a certain independent variable significantly affects a dependent variable, their spatial distributions should exhibit similarity[49]. This method can assess the spatial differentiation of single variables as well as detect interactions between two variables. The explanatory power of the geographical detector analysis is measured by the q value, represented by the following expression:

$$q = 1 - \left(\sum_{h=1}^{L} N_h \sigma_h^2 / N\sigma^2\right)$$

The q value ranges between 0 and 1, with a higher q value indicating a greater explanatory power of the various factors on the spatial differentiation of rural settlements in Guangdong Province. In the formula, L represents the strata of factor X, which refers to classification or zoning. N_h and N denote the number of units in stratum h and the entire region, respectively. σ_h^2 and σ^2 are the variances of Y values in stratum h and the entire region, respectively.

This study applies the GD method to explore the primary driving factors behind the spatial pattern evolution of rural settlements in Guangdong Province. Additionally, the factor interaction method is employed to investigate the synergistic effects of two influencing factors on the spatial evolution of rural settlements, determining whether their impact is mutually independent or not. The calculation principle involves first computing the q values for factors X1 and X2 concerning the spatial characteristics of rural settlements in Guangdong, then calculating the q value during their interaction, and finally comparing the interaction types of q(X1), q(X2) and q(X1∩X2). The specific research workflow is shown in Fig. 3.

Selection and processing of driving factors
The evolution of the spatial pattern of rural settlements is a complex process influenced by the interaction of multiple factors, including natural environment and socioeconomic conditions. Building upon existing research, and considering the practical situation of the study area and the availability of data, this study selects 11 driving factors across four dimensions: natural conditions, economic conditions, social conditions, and locational conditions (as shown in Table 1)[50–52]. All influencing factors are rasterized in ArcGIS, and a uniform projection coordinate system is applied, with continuous variables discretized for analysis.
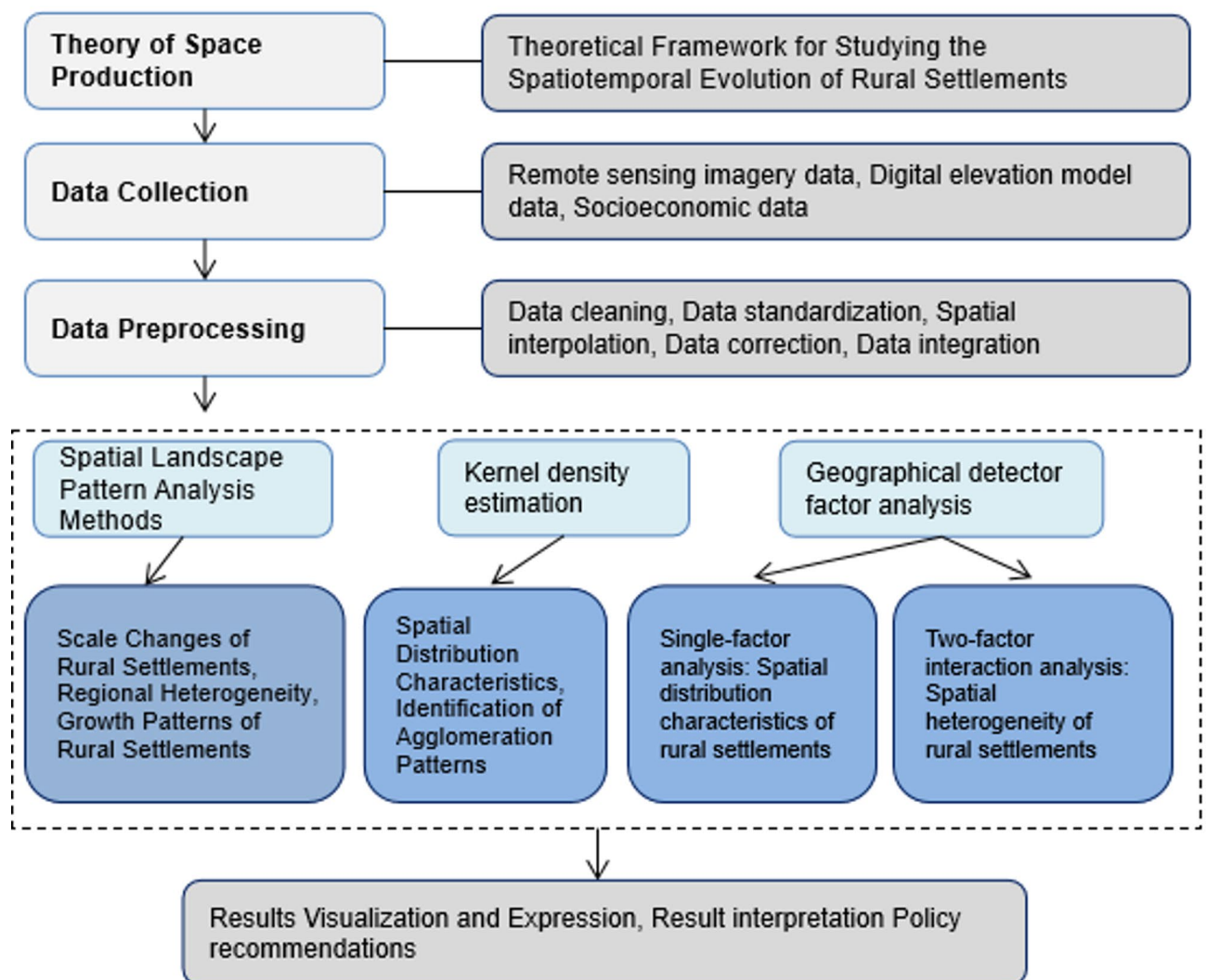

Fig. 3. Flowchart of research methodology.

		Factors	Index description
Dependent variables	Convergence	Agglomeration degree of rural settlement Y1	Average nearest neighbor index of rural settlements
	Scale	Scale of rural settlement Y2	The average patch area of rural settlements (km^2)
	Density	Density of rural settlement Y3	Patch density of rural settlements (PCS/km^2)
Driving factors	Natural factors	Altitude X1	Elevation (m)[53]
		Slope X2	Topographic slope (°)[53]
		Precipitation X3	Annual precipitation (mm)[54]
	Economic factors	Agricultural output value X4	Total annual agricultural production (yuan)[55]
		Per capita disposable income X5	Per capita disposable income statistics (yuan)[56]
		Per capita GDP X6	The gross domestic product/total population of the town (yuan)[57]
	Social factors	Urbanization rate X7	Non-agricultural population/total population (%)[58]
		Population density X8	Total population/area (person/km^2)[59]
	Locational factors	Distance from river X9	Distance from rural settlements to rivers (km^2)[60]
		Distance from road X10	Distance from rural settlements to roads (km^2)[61]
		Distance from the town center X11	Distance from rural settlements to urban centers (km^2)[62]

Table 1. Factor index system of spatial pattern evolution of rural residential areas in Guangdong Province.

	NP			TA (km^2)			MPS (km^2)		
	2002	2012	2022	2002	2012	2022	2002	2012	2022
Guangzhou	1306	898	639	334.09	256.39	344.73	0.26	0.29	0.54
Shenzhen	143	132	43	40.75	28.08	73.84	0.28	0.21	1.72
Foshan	869	587	469	309.87	206.48	238.49	0.36	0.35	0.51
Dongguan	595	237	173	497.84	91.53	183.81	0.84	0.39	1.06
Zhongshan	174	107	47	93.6	59.84	60.33	0.54	0.56	1.28
Zhuhai	112	108	94	29.5	52.62	76.33	0.26	0.49	0.81
Huizhou	1189	1173	555	246.74	263.3	269.26	0.21	0.22	0.49
Zhaoqing	2120	2081	2050	206.2	210.21	214.98	0.1	0.1	0.1
Jiangmen	1718	1672	1259	341.38	311.3	281.2	0.2	0.19	0.22
Shantou	563	567	480	216.92	172.26	286.03	0.39	0.3	0.6
Chaozhou	746	743	537	120.21	135.33	148.06	0.16	0.18	0.28
Jieyang	1720	1672	1319	244.98	229.67	267.91	0.14	0.14	0.2
Shanwei	848	836	422	91.21	89.77	66.67	0.11	0.11	0.16
Maiming	3523	3494	3528	525.63	531.25	555.98	0.15	0.15	0.16
Yangjiang	1507	1494	1455	190.29	181.65	195.44	0.13	0.12	0.13
Zhanjiang	3576	3549	3607	675.44	638.6	668.41	0.19	0.18	0.19
Shaoguan	1479	1476	1219	169.68	172.27	161.77	0.11	0.12	0.13
Yunfo	1492	1433	1413	181.83	181.23	186.68	0.12	0.13	0.13
Heyuan	483	486	286	55.09	60.89	50.34	0.11	0.13	0.18
Qingyuan	1934	1903	1588	234.18	227.81	193.02	0.12	0.12	0.12
Meizhou	977	985	486	131.02	131.56	67.62	0.13	0.13	0.14
Total	27,074	25,633	21,669	4936.45	4232.04	4590.9	0.18	0.17	0.21

Table 2. NP,TA,MPS of Rural Settlements in Guangdong Province (2002–2022).

Results

Temporal evolution of rural settlement system

Overall transformation patterns (2002–2022)

Over the past two decades, rural settlements in Guangdong Province have undergone a significant transformation, characterized by distinct phases (as shown in Table 2). Data extracted from remote sensing imagery reveal a consistent decline in the number of rural settlement patches (NP), underscoring the province's urbanization initiatives. From 2002 to 2012, the number of rural settlement patches decreased by 1441, a 5.32% reduction, while the total area (TA) decreased by 704.44 km^2, and the mean patch size (MPS) fell by 1.72 km^2. This initial period reflected a consolidation phase, with smaller, less efficient settlements being phased out. However, the subsequent period from 2012 to 2022 witnessed a shift, with NP continuing to decline by 3064 patches (14.06%), but both TA and MPS exhibited upward trends, increasing by 8.47% and 28.48%, respectively. This U-shaped pattern in TA and MPS indicates a move towards larger, more strategically planned rural communities, better integrated with the urban economy.

Strategic restructuring process

The transformation of rural settlements in Guangdong is far from uniform, with significant spatial differences across prefectural municipalities. From 2002 to 2012, most cities experienced a decline in NP, with only Heyuan and Shantou showing slight increases. However, the most significant changes were concentrated in the Pearl River Delta (PRD) region. The period from 2012 to 2022 saw a more pronounced decline in NP across all cities except Maoming and Zhanjiang, with the downward trend rapidly extending from the PRD to the eastern and northern regions. In terms of TA, eight cities saw an increase from 2002 to 2012, led by Zhuhai's nearly 80% growth, while 13 cities, particularly within the PRD, experienced a decrease. From 2012 to 2022, TA generally increased across most cities, with Shenzhen and Zhuhai seeing increases of over 100%, while Meizhou and Shanwei saw reductions of 48.60% and 25.73%, respectively. This divergence underscores the core-periphery dynamics at play, with the PRD leading in rural modernization while other regions face challenges in adapting to changing economic landscapes.

The increase in MPS is significantly associated with policies promoting the relocation and consolidation of rural settlements. Cities within the PRD have been more successful in leveraging these policies to create larger, more efficient rural communities, often integrated with urban development plans. Shenzhen, for example, saw the largest increase in MPS at 514.29%, reflecting its efforts to consolidate smaller settlements into larger, more economically viable units. However, the varying success rates across the province also highlight the need for tailored policy approaches that consider the unique economic and social contexts of different regions. While consolidation policies may be effective in driving modernization in the PRD, they may exacerbate disparities in less developed regions, necessitating targeted support and investment to ensure equitable rural development.

Regional differentiation in settlement development

Core-periphery development dynamics

The transformation of rural settlements across Guangdong's four regions reflects their unique development pathways, shaped by varying levels of economic development, urbanization pressure, and policy implementation capacity. The PRD, as the province's economic core, exemplifies an aggressive rural restructuring model, marked by substantial settlement consolidation (−14.96% in patch numbers during 2002–2012, followed by −23.82% in 2012–2022). This intensive consolidation pattern reflects the region's response to rapid industrialization and urban expansion, where rural land carries high economic premium and faces strong development pressure.

A clear core-periphery pattern has emerged in settlement transformation. While the PRD region pursued intensive consolidation, peripheral regions demonstrated more resistance to change, particularly evident in West Guangdong's divergent trend (0.62% increase in patch numbers during 2012–2022). This spatial disparity reflects not merely economic gaps but fundamentally different development contexts: the PRD's settlement consolidation is driven by urban expansion and industrial upgrading, while peripheral regions' resistance to consolidation stems from weaker urbanization pressure and the need to maintain rural population stability.

Regional transformation trajectories

According to Table 3, the changing settlement morphology, particularly the mean patch size (MPS), reveals the varying capacity of regions to modernize rural communities. The PRD's significant increase in MPS (54.61% in 2012–2022) indicates a shift toward more efficient, concentrated rural settlements supporting modern agricultural production and rural–urban integration. East Guangdong's remarkable MPS growth (69.70%) suggests successful policy implementation in settlement modernization, while the modest changes in West and North Guangdong reflect their constraints in rural transformation.

The divergent patterns in total settlement area (TA)—U-shaped in the PRD, East, and West Guangdong versus inverted U-shaped in North Guangdong—highlight how regions differently adapt to provincial rural restructuring policies. The PRD's pattern of initial contraction followed by planned expansion demonstrates a mature development trajectory, while North Guangdong's reverse pattern reflects its unique challenges in maintaining rural vitality amid population outflow and economic constraints.

Spatial reorganization and integration

Settlement pattern typology

The evolution of rural settlements in Guangdong demonstrates a complex transformation that extends beyond simple expansion or contraction. Based on Table 4, settlement patterns follow four distinct types as identified in previous research[50,63]: expansion (increased numbers and area), integration (decreased numbers but increased area), contraction (increased numbers but decreased area), and reduction (decreased numbers and decreased

Index	NP		TA		MPS		
Periods	2002–2012 (%)	2012–2022 (%)	2002–2012 (%)	2012–2022 (%)	2002–2012 (%)	2012–2022 (%)	2002–2022 (%)
Pearl River Delta	− 14.96	− 23.82	− 29.53	17.79	− 17.13	54.61	28.12
Eastern Guangdong	− 1.52	− 27.76	− 6.87	22.59	− 5.44	69.70	60.48
Western Guangdong	− 0.80	0.62	− 2.86	5.06	− 2.08	4.41	2.24
Northern Guangdong	− 1.29	− 20.55	0.25	− 14.78	1.56	7.26	8.94
Guangdong Province	− 5.32	− 15.46	− 14.27	8.48	− 9.45	28.32	16.20

Table 3. The scale Changes of rural settlements in four regions of Guangdong Province.

Regiongs	cities	2002–2012	2012–2022
Pearl River Delta region (from reduction to integration)	Guangzhou	Reduction	Integration
	Shenzhen	Reduction	Integration
	Foshan	Reduction	Integration
	Dongguan	Reduction	Integration
	Zhongshan	Reduction	Integration
	Zhuhai	Integration	Integration
	Huizhou	Integration	Integration
	Zhaoqing	Integration	Integration
	Jiangmen	Reduction	Reduction
Eastern Guangdong area (from reduction to integration)	Shantou	Contraction	Integration
	Shanwei	Reduction	Reduction
	Chaozhou	Integration	Integration
	Jieyang	Integration	Integration
Western Guangdong (from reduction to expansion)	Maoming	Integration	Expansion
	Yangjiang	Reduction	Integration
	Zhanjiang	Reduction	Expansion
Northern Guangdong (from integration to reduction)	Shaoguan	Integration	Reduction
	Yunfo	Reduction	Integration
	Meizhou	Expansion	Reduction
	Qingyuan	Reduction	Reduction
	Heyuan	Expansion	Reduction

Table 4. Changes in growth patterns of rural settlements in Guangdong Province from 2002 to 2022.

area). This classification reveals how economic development and policy interventions have shaped different trajectories across the province.

The PRD region, as shown in Table 4, has undergone a notable shift from reduction to integration. Cities like Guangzhou, Shenzhen, and Foshan have strategically consolidated smaller settlements into larger, more efficient communities while expanding their total area. Meanwhile, cities like Zhuhai, Huizhou, and Zhaoqing have maintained consistent integration patterns throughout the study period, suggesting stable development strategies. The contrasting case of Zhanjiang's shift toward expansion indicates a different development path, likely influenced by its emerging role as an industrial and port city.

The spatial distribution analysis, based on KDE with an optimal search radius of 10 km determined through minimum mean square error (Figs. 4, 5, 6), reveals increasingly concentrated settlement patterns. This search radius, being 5 times the bandwidth, is sufficient to cover the main influence range of the kernel function, resulting in more distinct stratification in the kernel density map. As evidenced in Table 5, the ANN index has steadily decreased from 0.411 to 0.386, with maximum kernel density values rising from 3.443 in 2002 to 4.682 in 2012, before adjusting to 3.808 in 2022. These trends, combined with consistently significant P values ($P < 0.0000$), demonstrate a clear and intensifying clustering pattern that aligns with broader regional development strategies.

The data from both tables collectively illustrate Guangdong's transition from simple reduction of scattered settlements to a more sophisticated integration approach. However, the divergent patterns between developed and less developed regions, particularly visible in Table 4's temporal comparison, highlight the need for more nuanced, region-specific development strategies. This evidence suggests that future policies must balance the efficiency gains of settlement consolidation with the unique developmental needs of each region.

Spatial distribution and clustering

The spatial analysis reveals a nuanced pattern of rural settlement distribution in Guangdong Province, characterized by distinct regional variations that reflect the interplay of economic development, geographical constraints, and policy interventions. Three high-density clustering areas emerge as focal points, with Western Guangdong maintaining its position as the region with the highest settlement concentration. This persistence of clustering in the west, despite province-wide urbanization trends, suggests the region's strong agricultural heritage and the effectiveness of rural development policies in maintaining stable community structures.

The temporal evolution of settlement patterns, particularly evident in the PRD region, tells a compelling story of economic transformation. The westward shift of the spatial clustering centroid from Guangzhou-Foshan to Yunfu between 2002 and 2022 reflects more than mere spatial reorganization—it represents the broader impacts of rapid urbanization and industrial development. This shift coincides with the PRD's economic diversification strategy and the implementation of rural revitalization policies, suggesting a deliberate effort to balance urban expansion with rural sustainability.

Regional disparities in settlement patterns highlight the complex challenges facing rural development planners. The northern region's characteristic low-density, large-scale clustering pattern, shaped by its mountainous terrain, exemplifies how geographical constraints continue to influence settlement possibilities
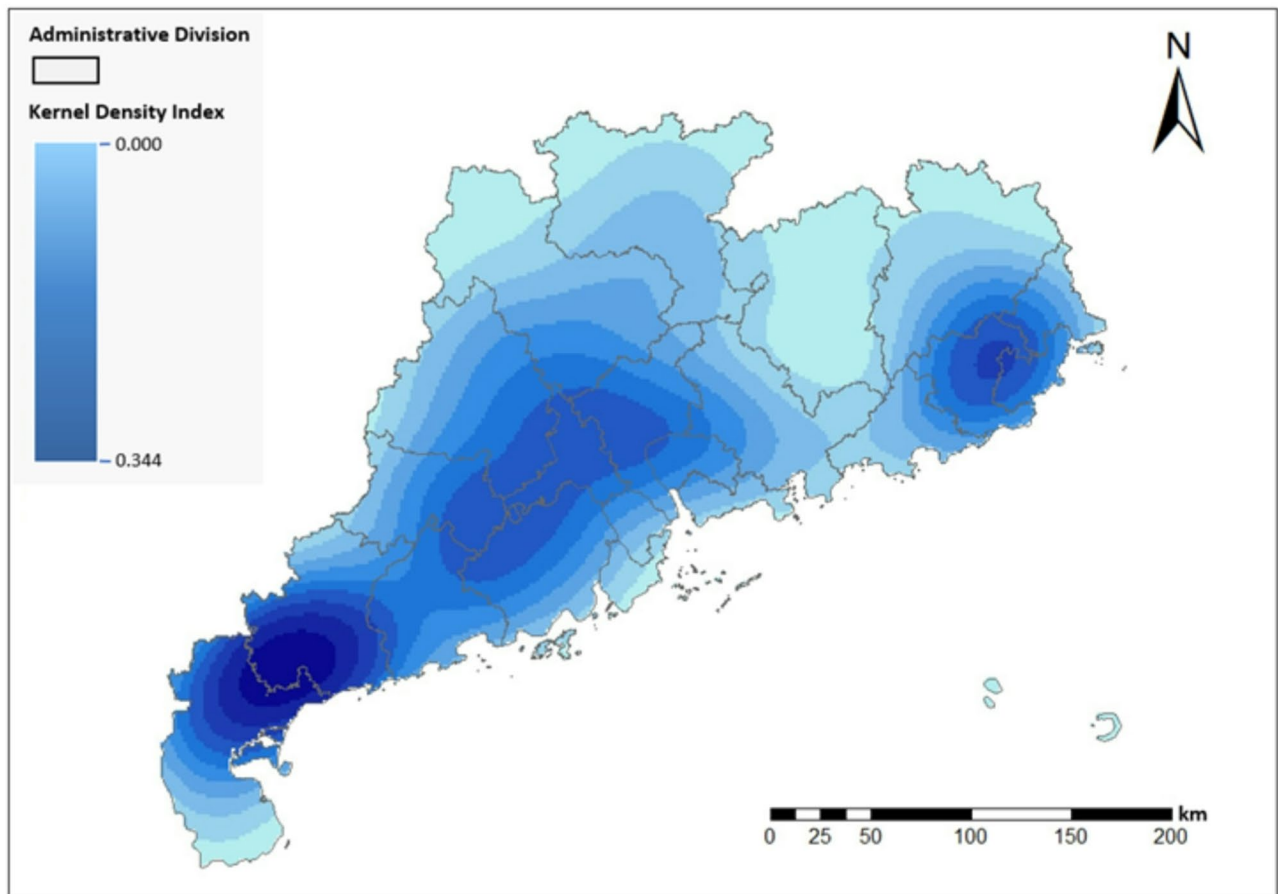
Fig. 4. Kernel density map of rural settlements in Guangdong Province, 2002.

even in an era of advanced urban planning. Meanwhile, the stability of Western Guangdong's settlement patterns, contrasting with the dynamic changes in the PRD, points to different development trajectories shaped by varying economic opportunities and policy priorities across regions.

These spatial and temporal variations, as illustrated in Table 5 and Figs. 4, 5 and 6, underscore the need for differentiated rural development strategies. While some regions demonstrate resilience in traditional settlement patterns, others show significant transformation in response to urbanization pressures. This diversity suggests that future rural planning must balance standardized development approaches with locally-adapted solutions that consider each region's unique geographical, economic, and social characteristics.

Analysis of driving factors for the spatial evolution of rural settlements based on geographical detector

Single-factor influences: from natural dependencies to socioeconomic drivers

The analysis reveals a significant shift in the driving forces behind rural settlement patterns over the past two decades (Table 6). Initially dominated by agricultural output (X4) and proximity to water resources (X9) in 2002, the influencing factors have evolved to encompass a broader spectrum of socioeconomic variables by 2022. This transformation reflects the region's transition from traditional agricultural dependencies to a more complex, urbanization-driven development model. The increasing influence of urbanization rate (X7) and transportation accessibility (X10) particularly demonstrates how rural settlement patterns have become increasingly responsive to urban development pressures and regional connectivity. The persistence of precipitation (X3) as a significant factor throughout the study period, especially after 2012, underscores the enduring importance of natural conditions in shaping settlement patterns, despite advancing urbanization. This suggests that while socioeconomic factors have gained prominence, fundamental environmental constraints continue to shape the spatial organization of rural communities.

Interactive effects: complex interplay of natural and socioeconomic factors

The interaction detection results (Table 7) reveal increasingly complex relationships among driving factors. The evolution from simple binary interactions in 2002 (such as agricultural output and river proximity) to more sophisticated multi-factor relationships by 2022 reflects the growing complexity of rural development dynamics. Notably, the strong interaction between precipitation (X3) and per capita disposable income (X5)
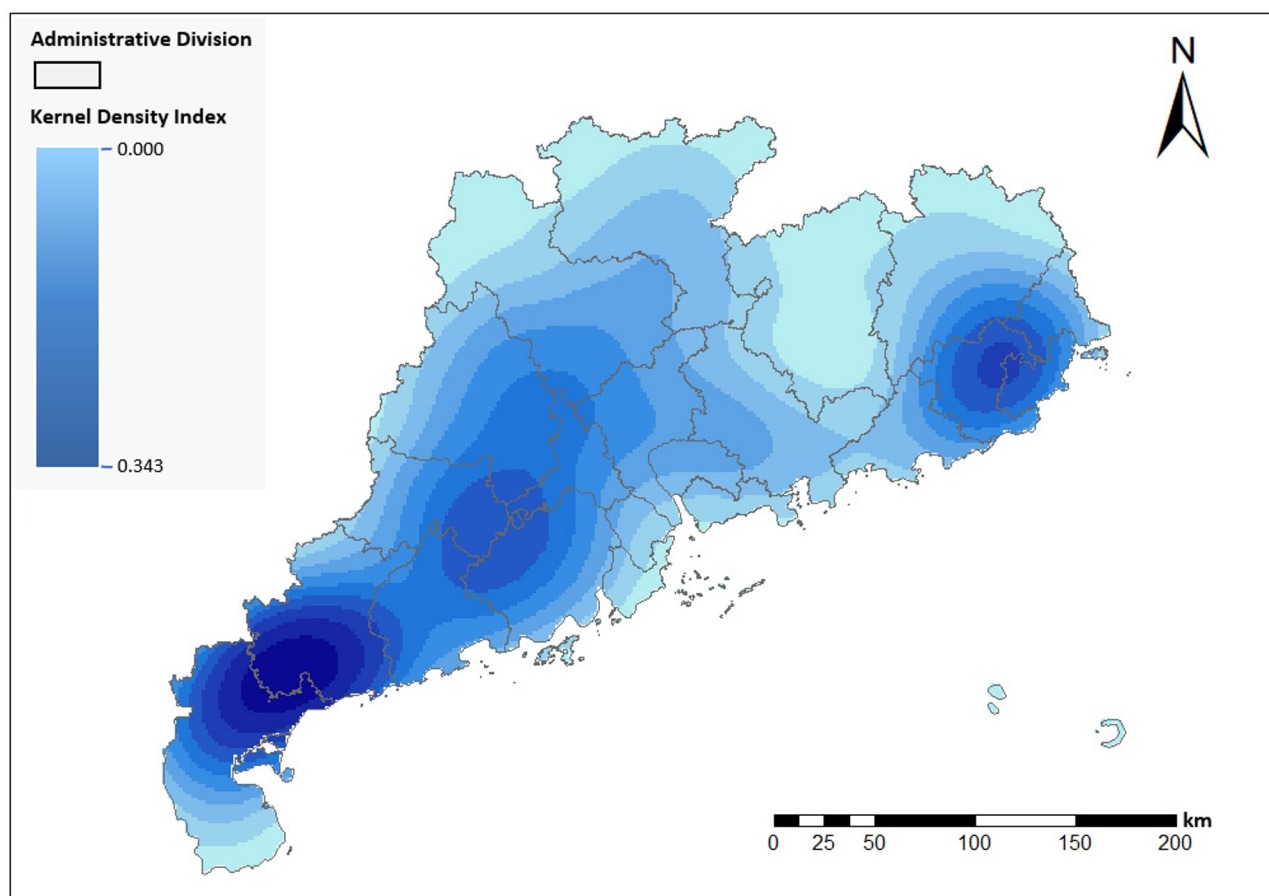
Fig. 5. Kernel density map of rural settlements in Guangdong Province, 2012.

in 2022 (q-value 0.96) suggests that economic development has become increasingly intertwined with natural environmental conditions.

The changing patterns of factor interactions mirror the broader transformation of rural settlement development over the study period. In the early stages, interactions primarily revolved around agricultural production capabilities and basic accessibility factors, reflecting the traditional rural economy's characteristics. As development progressed through 2012, urbanization-related factors began to exert stronger interactive effects, signaling the growing influence of urban expansion and modernization on rural settlements. By 2022, the interaction patterns had evolved to reflect a more nuanced and balanced influence of environmental, economic, and social factors, indicating a mature stage of rural–urban integration.

This temporal progression suggests a gradual transformation from a naturally constrained settlement system to one shaped by the complex interplay of urbanization, economic development, and environmental conditions. The consistently high interaction values for distance to town centers (X11) across different periods indicates the persistent importance of spatial proximity to urban areas in shaping rural settlement patterns, even as other influences have evolved.

The findings demonstrate that rural settlement evolution in Guangdong Province has transitioned from being primarily determined by natural and agricultural factors to being shaped by a more complex web of socioeconomic and environmental interactions, reflecting broader regional development trends and urbanization processes.

Discussion
The significant impact of urbanization on the distribution patterns of rural settlements
The results presented in the previous section highlight several key insights, which we now discuss in the context of broader theoretical and practical implications. According to the case of Guangdong, the degree of settlement aggregation is increasingly influenced by the level of urbanization. The distance between rural settlements and urban centers has become a significant locational factor affecting the scale of these settlements, while socioeconomic factors have replaced natural factors as the primary determinants of settlement density. In the dual-factor analysis, elements closely related to urbanization—such as the distance from rural settlements to urban centers, transportation conditions, and the synergistic effects among other factors—have intensified, becoming the main driving forces behind the scale and density of rural settlements. In short, urbanization directly influences the evolution of rural settlements. Globally, the relationship between urbanization and
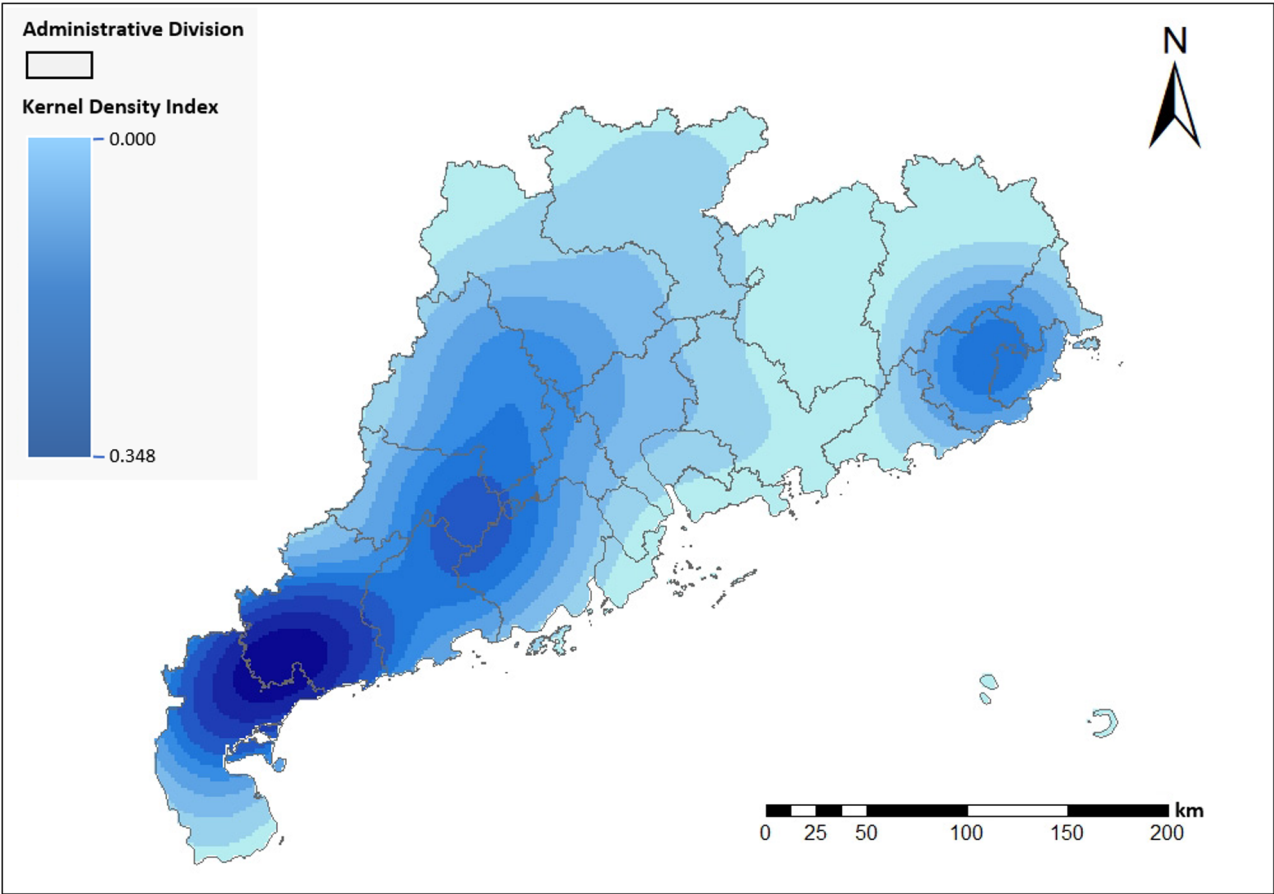
Fig. 6. Kernel density map of rural settlements in Guangdong Province, 2022.

Year	ANN	Z	p	Mean kernel density	Maximum kernel density
2002	0.411	− 61.81007	0.0000	1.578	3.443
2012	0.396	− 66.20744	0.0000	2.334	4.682
2022	0.386	− 69.76967	0.0000	2.001	3.808

Table 5. The index of Average nearest neighbor (ANN) and Nuclear Density Analysis of rural settlements in Guangdong Province.

		X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11
Y1	2002	0.20	0.22	0.50	0.64**	0.30	0.38	0.43	0.21	0.73**	0.48	0.23
	2012	0.21	0.22	0.69***	0.56*	0.61**	0.51**	0.54**	0.48	0.25	0.52**	0.43
	2022	0.22	0.20	0.84***	0.61**	0.48**	0.48*	0.67***	0.39	0.36	0.45*	0.40
Y2	2002	0.44*	0.64**	0.28	0.17	0.37	0.57**	0.38	0.29	0.23	0.75***	0.59**
	2012	0.59***	0.66***	0.45*	0.33	0.24	0.42	0.32	0.21	0.47	0.63*	0.58**
	2022	0.53**	0.65**	0.43*	0.30	0.29	0.25	0.29	0.48	0.51*	0.61*	0.47
Y3	2002	0.14	0.33	0.35	0.40	0.23	0.28	0.12	0.65*	0.62*	0.43	0.62***
	2012	0.09	0.30	0.68***	0.50	0.56	0.35	0.31	0.62**	0.30	0.51**	0.47
	2022	0.14	0.30	0.74**	0.51*	0.31	0.26	0.52*	0.56*	0.54*	0.46*	0.57***

Table 6. Q values of factor detection in Guangdong Province from 2002 to 2022. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

Dependent variable	Time	Top Ten Factor Interaction Results
Y1	2002	X4∩X9(0.91), X4∩X7(0.89), X4∩X10(0.88), X10∩X11(0.88), X4∩X11(0.87), X9∩X11(0.86), X9∩X10(0.85), X4∩X8(0.83), X3∩X11(0.82), X7∩X8(0.82)
	2012	X7∩X11(0.96), X3∩X11(0.94), X3∩X6(0.92), X3∩X7(0.92), X3∩X9(0.92), X5∩X7(0.92), X3∩X5(0.91), X4∩X9(0.91), X3∩X8(0.90), X4∩X8(0.90)
	2022	X3∩X5(0.96), X3∩X8(0.94), X3∩X7(0.93), X3∩X6(0.92), X6∩X8(0.92), X3∩X4(0.91), X6∩X10(0.91), X3∩X10(0.90), X4∩X6(0.90), X8∩X11(0.90)
Y2	2002	X10∩X11(0.91), X7∩X10(0.89), X7∩X11(0.86), X2∩X9(0.86), X3∩X10(0.85), X2∩X6(0.84), X8∩X10(0.84), X2∩X10(0.83), X9∩X10(0.83), X4∩X10(0.83)
	2012	X3∩X10(0.94), X4∩X10(0.90), X1∩X6(0.84), X1∩X3(0.83), X1∩X11(0.81), X2∩X11(0.81), X10∩X11(0.81), X2∩X6(0.79), X2∩X3(0.77), X4∩X6(0.77)
	2022	X3∩X4(0.88), X7∩X10(0.85), X2∩X4(0.84), X2∩X7(0.83), X2∩X3(0.82), X1∩X10(0.81), X3∩X6(0.78), X6∩X10(0.78), X2∩X10(0.77), X10∩X11(0.77)
Y3	2002	X9∩X11(0.91), X10∩X11(0.89), X9∩X10(0.83), X4∩X11(0.83), X4∩X10(0.80), X3∩X11(0.80), X7∩X9 (0.80), X4∩X8 (0.79), X7∩X8(0.79), X8∩X9(0.76)
	2012	X4∩X8(0.94), X4∩X10(0.92), X4∩X5(0.89), X5∩X9(0.89), X5∩X11(0.88), X8∩X9(0.88), X8∩X11(0.88), X7∩X8(0.87), X7∩X9(0.87), X4∩X6(0.86)
	2022	X3∩X11(0.92), X6∩X11(0.91), X4∩X11(0.90), X7∩X11(0.89), X9∩X11(0.89), X4∩X8(0.89), X4∩X6(0.86), X4∩X9(0.86), X6∩X10(0.86), X4∩X7(0.85)

Table 7. Interactive detection results of driving factors of spatial evolution of rural settlements in Guangdong Province.

rural development is closely intertwined. The rural restructuring in Guangdong represents a unique hybrid transformation that differs from the classical post-productivist countryside debate. While post-productivism in Western contexts often emphasizes the shift from agricultural production to consumption-oriented landscapes, recent studies show that China's rural transformation, particularly in Guangdong, exhibits a concurrent development of both productivist and post-productivist elements[64]. This distinctive pathway is further evidenced by analysis of China's rural revitalization strategy, which demonstrates how state-led initiatives are creating a new form of multifunctional countryside that maintains productive capacity while incorporating post-productivist features[65]. This pattern mirrors similar transformations observed in Latin America, where urbanization has fundamentally altered rural settlement patterns and triggered massive rural-to-urban migration[66]. Studies across developing regions have also shown that the intensity of rural transformation is particularly pronounced in rapidly urbanizing areas, where the integration of urban–rural resources has become a common development trajectory[67]. In suburban areas, phenomena such as "counter-urbanization" and "rural gentrification" have emerged, while villages distanced from urban centers inevitably face population decline and rural deterioration[68].

Urbanization policies at both the central and local levels have had a profound impact on the evolution of rural settlements. Under the impetus of policies promoting urban–rural integration, governments at all levels have accelerated the urbanization process and integrated urban and rural land resources. In 2001, Guangdong Province initiated the "village committee transformation to neighborhood committee (cungaiju)" policy, which adjusted administrative divisions to incorporate more rural land into urban areas. This policy has spread from the Pearl River Delta to surrounding regions, resulting in a continuous decrease in the number of rural settlements, a trend that has extended from the Pearl River Delta to other areas. Between 2002 and 2012, the area of rural settlements rapidly declined, including the well-known Tongzhou District near Beijing[69].

In 2009, Guangdong Province launched a distinctive urban renewal model known as "Three Oldies(old towns, old factories, old villages) Transformation (sanjiu gaizao)". Together with the "Rural Revitalization Strategy" vigorously implemented in 2018, these policies have sparked a wave of rapid rural development. As farmers' incomes increased, there was a widespread trend of building new houses. The coexistence of "new" and "old" villages has led to a growth trend in the area of most rural settlements starting in 2010, shifting their growth model from "reduction" to "integration".

The spatial transformation of rural settlements in Guangdong Province exemplifies the complex interplay between policy implementation and regional characteristics. Through the lens of spatial production theory[45], the PRD region demonstrates how economic development and policy interventions jointly reshape rural spaces. Local governments in the PRD, driven by "land finance" imperatives, have actively promoted urbanization through rural land acquisition and the creation of "urban villages." While this initially led to settlement reduction, the "Three Oldies Transformation" policy has created new development opportunities. The upgrading of rural industrial parks has attracted migrant populations, while increased rental demand has encouraged residential expansion. These factors have collectively shifted the trajectory of PRD rural settlements toward expansion since 2012.

Northern Guangdong, however, presents a contrasting case of "reduction-type" transformation, highlighting how geographical and economic constraints can limit policy effectiveness. The region's challenging topography has historically resulted in fragmented settlement patterns and smaller settlement scales. Limited industrial development and infrastructure constraints—as evidenced by a road network density of 1.10 km/km^2 in 2020, 21.2% lower than other regions in Guangdong—have compounded these challenges[70]. The household registration reform, while beneficial in principle, has accelerated population outflow from these economically disadvantaged areas, further intensifying the reduction in settlement areas. This regional divergence in settlement transformation patterns underscores how the effectiveness of rural development policies is significantly mediated by local geographical and economic conditions.

Policy implications of spatial reorganization of different types of rural settlements

The spatial reorganization of rural settlement spatial patterns is crucial for sustainable development in Guangdong Province. In recent years, rural settlements throughout China have experienced a general trend of expansion with low-density growth[71]. Despite strict land use regulations, the tension between urban and rural construction land has become a significant constraint on rural development. Therefore, it is imperative to optimize the spatial layout of rural settlements to support China's socioeconomic progress. This paper indicates that natural and locational factors are the primary drivers of changes in the spatial scale of rural settlements in Guangdong. Consequently, optimizing the spatial layout can be approached by enhancing the functions of central towns and villages. For instance, the recent provincial initiatives encouraging the development of administrative units at the county level or below can be utilized to prioritize the development of urban public infrastructure and services in central towns and villages. This will strengthen the bidirectional connections between these towns and both urban and rural areas, facilitating rural development towards central towns and villages, thereby breaking the traditional extensive development pattern. In the future development of Guangdong's newly urbanized, high-density areas such as Zhanjiang and Yunfu should be given greater importance. In summary, the spatial layout reorganization of rural settlements is essential for addressing land constraints and fostering sustainable rural development in Guangdong.

The optimization and restructuring of rural settlements vary across different development stages in Guangdong Province. Rural settlements in economically developed areas of Guangdong predominantly follow an "integration" mode characterized by a decrease in the number of settlements and an expansion in area. For these settlements, it is necessary to control their sprawling tendencies and enhance the core leadership role of county towns in the development of rural settlement systems. This can be achieved by establishing a four-tier transmission system of "county—town—central village—general village," along with a four-tier linkage system for industry, market, capital, and public services. Encouraging cluster development in suitable rural areas can maximize the utilization of land resources. In contrast, rural settlements in economically underdeveloped areas tend to follow a "reduction" mode, where both the number and area of settlements decrease. These areas often have small county town scales, limited aggregation capabilities, low levels of economic development, and inadequate modernization in agriculture and industry, coupled with limited public service coverage. Future development should focus on linking counties, towns, and villages through major transportation routes to form a development chain. This will integrate previously scattered and weak village groups into a whole to improve facilities and enhance the competitiveness of rural industries. Additionally, leveraging opportunities from the use of the internet and ecological and cultural resources can promote the integration of the different types of industries. Tailored approaches to optimizing rural settlements based on their development stages are vital for achieving balanced and sustainable rural growth in Guangdong.

Beyond traditional geographical factors that shape village spatial patterns, climate change has emerged as a critical consideration in rural settlement planning. This alignment reflects both national priorities, as evidenced in the National Rural Revitalization Strategy Plan (2018–2022), and provincial leadership, with Guangdong being China's first province to implement a climate adaptation plan in 2015. Our analysis of spatiotemporal changes in rural settlements from 1992 to 2022 suggests that climate resilience must be integrated into the existing spatial reorganization framework, particularly within the context of different development modes identified earlier.

The integration of climate considerations into village planning requires a differentiated approach that aligns with the previously discussed development modes. For settlements following the "integration" mode, particularly in the Pearl River Delta region, climate risk assessments should inform the consolidation process. Based on historical disaster data, settlements in high-risk areas should be gradually relocated or functionally replaced[72]. This approach can be implemented through resilient spatial management mechanisms, including ecological buffer zones and disaster risk areas in county-level territorial planning. The four-tier transmission system can be enhanced by incorporating region-specific climate adaptation strategies: strengthening flood management in the Pearl River Delta's suburban villages, implementing storm surge protection in coastal economic zones, and emphasizing soil and water conservation in northern ecological zones. For areas following the "reduction" mode, climate adaptation measures should be integrated with existing plans for settlement consolidation, ensuring that remaining settlements are both sustainable and resilient.

To operationalize these strategies, a comprehensive climate-adaptive system should be developed within the existing spatial reorganization framework. This includes embedding "sponge village" concepts into rural construction, with adaptations tailored to local development modes. In integration-mode areas, emphasis should be placed on sophisticated infrastructure solutions that support higher-density development, while reduction-mode areas should focus on cost-effective, sustainable approaches. The four-tier linkage system can be enhanced through smart monitoring and early warning systems, leveraging county-level digital initiatives to create a coordinated response network. This integrated approach ensures that climate adaptation measures support both immediate resilience needs and longer-term spatial optimization goals, while maintaining consistency with the development trajectories of different regions in Guangdong Province.

Conclusions

This study provides a comprehensive analysis of the spatiotemporal dynamics of rural settlement evolution in Guangdong Province, revealing distinct regional disparities and evolutionary mechanisms. Our findings underscore the importance of tailored approaches to rural development and spatial planning. It is shown that the overall scale of rural settlements in Guangdong Province indicates a trend of reduction, with significant regional disparities. From 2002 to 2022, the number of rural settlements continuously declined, while the area of patches and the average patch area exhibited a pattern of first decreasing and then increasing. This conclusion aligns with findings from other studies[70]. The fluctuations in the scale of rural settlements demonstrate evident spatial disparities. Between 2002 and 2012, the regions with the most significant decline in the number of rural

settlements among the 21 prefecture-level cities were all located in the Pearl River Delta. In the following decade, the trend of declining settlement numbers spread from the Pearl River Delta to other regions, with almost all cities experiencing a decrease in the number of rural settlements. Concurrently, the total area and the average area of rural settlements showed an upward trend. Over the past 20 years, the number of rural settlements in all four regions of Guangdong has decreased. However, in the first 10 years, the Pearl River Delta experienced the largest reduction, while in the latter 10 years, only the Western Guangdong region saw an increase, with the other regions showing similar reductions. The area of rural settlements in the Pearl River Delta, Eastern Guangdong, and Western Guangdong exhibited a trend of first decreasing and then increasing, while Northern Guangdong showed a pattern of first increasing and then decreasing. Overall, the area in the Pearl River Delta and Northern Guangdong has declined, while the area in other regions has increased; the average area of settlements in the four regions has also increased, with Eastern Guangdong experiencing the most rapid growth.

The growth patterns of rural settlements in Guangdong exhibit spatiotemporal variability. The growth model of rural settlements in Guangdong has shifted from a "reduction" to an "integration", although the developmental trajectories differ across regions. The rural settlements in the Pearl River Delta and Eastern Guangdong have transitioned from a reduction type to an integration type, while those in Western Guangdong have shifted from a reduction type to an expansion type; in contrast, Northern Guangdong has transitioned from an integration type to a reduction type. Among the 21 cities, most economically developed cities have also shifted from a reduction type to an integration type, consistent with the overall developmental trend, whereas relatively underdeveloped areas have moved toward a reduction type. This trend aligns with general perceptions: economically developed regions require optimization of the spatial layout of rural settlements due to urgent demand for construction land driven by rapid urban expansion, resulting in a decrease in quantity and an increase in area; conversely, in relatively underdeveloped areas, population outflow and village consolidation lead to simultaneous decreases in both quantity and area.

The spatial distribution of rural settlements in Guangdong Province demonstrates an overall trend of agglomeration, which has also gradually intensified over time. The spatial layout of rural settlements in Guangdong presents a coexistence of high-density small-scale agglomeration and low-density large-scale agglomeration. Among the three high-density agglomeration zones, the Western Guangdong region exhibits the highest degree of agglomeration. Meanwhile, Northern Guangdong is characterized by a low-density, large-scale agglomeration pattern. Overall, the eastern and western regions are densely populated, while the spatial distribution in the northern mountainous areas is sparse. In conjunction with the findings drawn from existing literature, it is noteworthy that the highly populated center of spatial agglomeration in the Pearl River Delta has shifted from the Guangzhou-Foshan metropolitan area to the relatively remote city of Yunfu[73]. Similar spatial heterogeneity patterns have been observed in other developing countries, particularly in India, where studies across 146 urban centers have revealed significant inter-urban spatial inequality in living conditions, with clear geographic clustering of development indicators[32]. In Vietnam's Mekong Delta region, spatio-temporal analysis has shown comparable transformation patterns in rural landscapes, where settlement restructuring is driven by national agricultural transformation policies and local livelihood adaptations, resulting in distinct spatial clustering of development outcomes[74].

Decoupling from agricultural factors, the spatiotemporal evolution of rural settlements in Guangdong is influenced by multiple emerging driving factors, including natural, social, economic, and locational elements. Traditional influencing factors continue to play a role, but the impact of social and economic factors has become increasingly evident. In terms of the evolution of rural settlement agglomeration, the number of influencing factors has gradually increased, with natural factors such as precipitation gaining more influence while the impact of agricultural output has weakened. Natural factors like altitude, slope, and precipitation, along with locational factors such as distance to roads and urban centers, are the primary drivers of changes in the spatial scale of rural settlements in Guangdong Province. In terms of changes in the spatial density of rural settlements, the influence of natural factors is relatively weak, while locational and economic factors have become the main driving forces. Interaction detection among factors reveals that the interactions between driving factors exhibit nonlinear enhancement or dual factor enhancement, indicating that the combined effects of these driving factors are propelling the evolution of the spatial pattern of rural settlements in Guangdong Province. This research not only sheds light on the dynamics of rural settlements in Guangdong but also holds significant implications for other regions around the world experiencing similar transitions. Understanding the decoupling from agricultural influences and the rising importance of social, economic, and natural factors can inform rural development policies globally, enabling more sustainable and adaptive settlement planning in diverse contexts.

This comprehensive analysis of rural settlement evolution in Guangdong Province has provided significant insights into spatial patterns and mechanisms, yet several areas warrant further investigation. First, while our current methodology effectively captures static spatial patterns and their driving factors, it has limitations in simulating dynamic processes such as hollow village restructuring and suburban integration. This constrains our ability to predict how settlements might respond to the combined effects of new urbanization initiatives and rural revitalization strategies. Second, although the geographical detector method has successfully identified key influencing factors and their interactions, it cannot fully capture the complex synergies between policy changes, household decisions, and environmental risks. Of particular concern is the absence of climate change considerations in our analytical framework, especially regarding extreme weather events and their impact on settlement resilience. These limitations suggest promising directions for future research, particularly in developing integrated modeling approaches that combine multi-source data, agent-based simulations, and advanced machine learning techniques. Such methodological advances would enhance our understanding of the complex human-nature interactions shaping rural settlements, thereby providing more robust support for evidence-based policy making in rural development.

Data availability

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

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L.J.: conceptualization, writing—original draft, validation, formal analysis, investigation, data curation, methodology. Z.L.; writing—original draft, validation, formal analysis, investigation, data curation, methodology, validation, writing—review and editing, supervision. Y.L.: validation, investigation, visualization, project administration. All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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