

Research on the measurement and zoning of rural human settlements in economically developed areas under “nature-economy-society” coupling

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Research Article

Keywords: Rural living environment, “natural–economic–social” coupling, spatial differentiation, zoning control, Guangzhou city

Posted Date: March 18th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-8788878/v1>

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Additional Declarations:

No competing interests reported.

Competing interests

Authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

Author contributions

Shuyin Wu, Can Li, Ting Feng, Xiaodong Wang, Jiayi Zhuang(2025) Characteristics and Structural Differences in Land Use in Urban Villages. *Tropical Geography*, 45(10),1866-1876.

<https://doi.org/10.13284/j.cnki.rddl.20240745>.

Wu Linhao, Li can, Zhuang jiayi, Li Wei, Chen Wenguang, Kong xiangbin (2025) Spatio temporal characteristics and control zoning of the coupling between rural population hollowing out and farmland abandonment in Guangdong Province. *Transactions of the Chinese Society of Agricultural Engineering*, 41 (23), 231-242. <https://link.cnki.net/urlid/11.2047.S.20251112.1531.058>

Funding sources

(1) The National Natural Science Fund, (42371268), Research on the functional transformation mechanism and regulation mode of rural residential land

(2) Ministry of Education Humanities and Social Sciences, (22YJA630038), Research on the impact mechanism and control path of homestead utilization transformation

(3) Guangdong Philosophy and Social Science Foundation, (GD25CGG17) Transformation of rural homestead utilization: internal mechanism, realistic dilemma and governance path

Supplementary material

NONE

Data statement

The data set is provided by Geographic remote sensing ecological network platform([www. gisrs. cn](http://www.gisrs.cn)), Resource and environmental science and data center, Chinese Academy of Sciences and Baidu Maps Open Platform.

Acknowledgements

We are thankful to the The National Natural Science Fund, (42371268), “Research on the functional transformation mechanism and regulation mode of rural residential land”; Ministry of Education Humanities and Social Sciences, (22YJA630038), “Research on the impact mechanism and control path of homestead utilization transformation” ;Guangdong Philosophy and Social Science Foundation, (GD25CGG17), “Transformation of rural homestead utilization: internal mechanism, realistic dilemma and governance path”.

Research on the measurement and zoning of rural human settlements in economically developed areas under “nature-economy-society” coupling

Abstract: Under the framework of the Global Sustainable Development Goals (SDGs), rural residential quality of life (REQL) has become a core issue in measuring regional coordination and sustainable development. For economically underdeveloped or ecologically fragile areas, scholars have focused on natural and material space attributes, ignoring the complexity of REQL in economically developed areas. In this study, a comprehensive analysis framework based on “nature–economy–society” coupling is established, Guangzhou city, Guangdong Province, China, is selected as a case study, the spatial differentiation trend of regional REQL is analyzed, a coupled coordination degree model is used to reveal the relationships between different dimensions of REQL, and a bivariate spatial analysis model is constructed to control the partitioning of REQL. The results show that (1) the REQL in Guangzhou is at the upper-middle level, with patterns of “strong in the south and weak in the north” and “the plains are better than the hills”; (2) the “economy-society” system is the most closely coupled, and economic development significantly promotes the improvement of the social service level. The degree of coordination of the “nature-society” system is the lowest, and the ecological advantages have not been effectively transformed into public service capabilities. (3) Based on the comprehensive characteristics of quality and coordination, four types of control are considered: “comprehensive leading optimization areas”, “collaborative upgrading cultivation areas”, “potential recovery and strengthening areas” and “key

reconstruction intervention areas”.

Keywords: Rural living environment; “natural–economic–social” coupling; spatial differentiation; zoning control; Guangzhou city

1 Introduction

Rural residential environmental quality of life (REQL) is a comprehensive index encompassing the interactions among the environment, the economy, society and the living space in a rural regional system. Under the framework of the Global Sustainable Development Goals (SDGs), research on REQL has become important for promoting equity and transforming development (Doxiadis, 1975), not only for poverty alleviation (Liu et al., 2019) and health (Tong et al., 2022) but also for inclusive growth (Chirisa & Nel, 2022), helping to overcome the imbalance between urban and rural development (Mera, 1979; Wang et al., 2025). His research is directly linked to several core goals, including “Good Health and Well-being” (SDG 3) (Shekhar et al., 2019), “Clean Water and Sanitation” (SDG 6) (Roundy, 1985; Pachori, 2016; Huttinger et al., 2017), “Affordable and Clean Energy” (SDG 7) (Nathwani & Kammen, 2019), “Sustainable Cities and Communities” (SDG 11) (Lin & Hou, 2023; Markey et al., 2008), “Climate Action” (SDG 13) (Kumar et al., 2025; Magadza, 2000) and “Terrestrial Ecological Life” (SDG 15) (Zhang, 2020a), which together highlight the critical role of human settlement quality in health security, resource use, environmental security and ecological protection.

As a typical complex natural–economic–social index, REQL is influenced by

resource constraints (Li Y et al., 2022), ecological degradation (Zhang, 2020b–d), environmental pollution (Abbass et al., 2022; Cheng et al., 2025), weak infrastructure (Hosseini et al., 2024) and spatial functional imbalance (Aimar et al., 2021; Ran et al., 2024). These issues are intertwined, reflecting the complex interactions among natural, economic, and social systems and revealing the potential contradiction between insufficient ecological resilience (Wang C et al., 2022) and a lack of social equity in the process of achieving sustainable development. These contradictions restrict the realization of the above SDGs to varying degrees. In-depth studies of the structural characteristics, driving mechanisms and optimization paths of rural human settlements not only help reveal the coupling relationships among nature, the economy, and social systems but also provide a scientific basis for understanding the interaction mechanisms among environmental quality, social equity and sustainable well-being. Systematic improvement of REQL is important for achieving comprehensive progress toward the SDGs (Islam, 2024) and promoting global ecological security and the common well-being of mankind (Islam, 2024).

REQL is directly related to the livelihood and well-being, health level and development opportunities of China's 460 million people in rural areas (Xu X & Sakai, 2024) and is also a key basis for promoting urban–rural integration and realizing rural revitalization strategies (Yuan et al., 2018; Han, 2019). At present, China is in a critical stage of simultaneous urbanization and ecological civilization construction (Meng F et al., 2021). On the one hand, the rural population is rapidly moving to urban areas (Xu D et al., 2020; Liu D et al., 2015; Gu et al., 2015), leading to prominent 'rural hollowing'

(Wang Y & Uekita, 2026; Liu Y.s et al., 2009), reductions in the vitality of rural development, and decreases in the quality of the living environment (Yu F, 2019). On the other hand, the government's continuous efforts to improve the rural living environment have significantly improved the conditions for rural development (Hu & Wang, 2020). In this process, the system encompassing rural human settlements and the environment is influenced by the weakening of endogenous power and the increase in external input, but its overall quality is still mainly tied to inherent structural contradictions. Therefore, system deconstruction and scientific evaluation of the development problems associated with REQL are of important theoretical and practical significance.

Existing research was mainly focused on the theoretical framework (Liu R et al., 2024), such as environmental quality (Yu et al., 2022), infrastructure conditions (Hu & Wang, 2020), and housing safety (Liu Z & Li, 2025). Evaluation systems have been constructed from the perspective of public service allocation (Pan et al., 2022) and have gradually incorporated residents' subjective feelings and level of satisfaction (Chen N (Chris) et al., 2019) to create an analysis framework that combines subjectivity and objectivity (Li X & Li H, 2021). Some studies have established theoretical frameworks through structural equation models and performed hard and soft assessments of rural human settlements (Zhao X et al., 2019). Researchers have confirmed that ecological and environmental factors have a notable impact on the quality of human settlements in fragile areas such as the arid and alpine parts of the western region of China (Wang P et al., 2021). In terms of research methods, evaluation techniques have shifted from

qualitative description to multimodel and data-driven analysis (Wang & Lu, 2018), and coupled coordination degree models (Hua & Cuiwei, 2024; Zhao W et al., 2024), fuzzy comprehensive evaluation methods (Jia et al., 2022; Wu et al., 2023), principal component analysis (Xiong & Zhang, 2021; Xiao-peng & Qi-ming, 2022) and spatiotemporal analysis technology based on GIS and remote sensing have been widely used (Jiménez et al., 2019; Chen R et al., 2014; Chen H et al., 2024; Zhao Y et al., 2023; Feng et al., 2022); moreover, new methods such as "three-life space" coupling (Meng L & Yan, 2025) and the fully permuted polygon comprehensive index approach (Chen Q et al., 2025) continue to expand the depth of research. Some scholars have also tried to extract quantitative indicators from policy texts (Li Y et al., 2022) to explore the relationship between the institutional environment and human settlement quality (Chen Y et al., 2023). However, several limitations exist in the existing research. First, most studies have focused on underdeveloped or ecologically fragile areas (Yin et al., 2023), while relatively insufficient attention has been given to rapidly transitioning areas such as economically developed areas and suburbs, making it difficult to fully reflect the diversity and complexity of China's rural living environment. Second, focus has been placed on the natural and material space dimensions, and the interaction mechanism between socioeconomic transformation (such as changes in employment structure, service accessibility, and population mobility) and the evolution of the living environment remains incompletely understood (Zhu et al., 2020). Third, the spatial scale of analyses is often a macroscale, such as using statistical data at the county level, and differences within villages supported by high-resolution data have not been

explored; this scale issue has restricted the development of refined management and classification policies.

Given the above issues, on the basis of the theory of human–nature relationships, human settlement–environment science and the concept of sustainable development, in this paper, a multidimensional comprehensive evaluation of the “nature–economy–society” system is performed, the mechanisms of social and economic processes in the evolution of human settlements are highlighted, and the spatial differentiation characteristics and formation logic of rural human settlements in areas with different development levels are revealed on the basis of high-resolution spatial data and in-depth research in typical regions to provide a scientific basis for promoting the precise governance, zoning and long-term development of rural human settlements in China.

2 Theoretical basis and analytical framework

The scientific measurement and spatial zoning of rural human settlements need to be based on a systematic understanding of their composition and evolutionary logic. On the basis of the coupling theory of “nature–economy–society”, an integrated analytical framework is proposed. According to the framework, the rural human settlement environment is a spatial representation of the intertwined interactions among nature, economy and society, and its quality and pattern differences are rooted in the differences in the coupled state, interaction intensity and degree of coordination of these three dimensions across different regions.

Under this framework, the natural dimension constitutes the ecological basis and

physical constraints of the human settlement environment, including mainly geographical conditions, resource endowments and ecological conditions, which fundamentally affect the distribution of settlements, land use methods and environmental bearing thresholds. The economic dimension reflects the material support and development level of the living environment, covering industrial structure, employment status, income level, infrastructure, etc., and its transformation profoundly affects the spatial form and functional organization of rural areas and quality of life there. The social dimension reflects the governance and coordination levels of the living environment and encompasses the interactions among man, nature and the economy through public services, governance mechanisms, community networks, cultural concepts, etc. In this context, the goal is to achieve a system that is orderly and sustainable.

These three dimensions do not exist independently but jointly shape the overall living environment through continuous interaction. Natural conditions constrain the possibilities and set boundaries for economic activities, which in turn affect the state of natural systems, while social dimensions are associated with guiding, regulating and adjusting this interaction process through institutions, technologies and culture. The different combinations, intensities and coordination levels among the three dimensions ultimately result in significant differences in the structure, function and quality of the living environment in space, which constitute the fundamental basis for systematic measurement and scientific partitioning.

Therefore, the measurement system introduced in this study closely corresponds

to the above three dimensions, and a comprehensive index system covering “natural base conditions”, “economic development level” and “social coordination ability” is constructed to comprehensively describe the state of rural human settlements. On this basis, comprehensive evaluations and spatial analyses of multiple indicators are performed to reveal the dominant characteristics, system coordination levels and spatial differentiation trends of human settlements in different regions to provide a theoretical basis and analysis tools for identifying different types of settlements and implementing classification guidance.

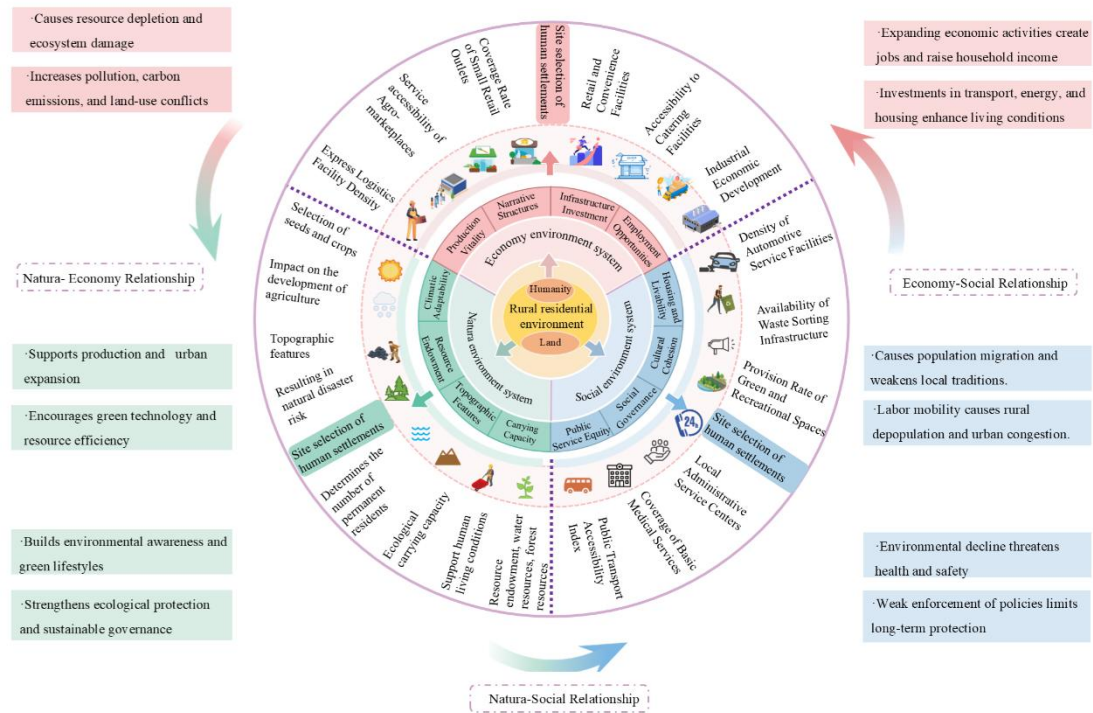


Fig. 1 Mechanisms that impact rural human settlement quality under “nature–economy–society” coupling

3. Data and methods

3.1 Indicator selection

On the basis of the theoretical framework of “nature–economy–society” coupling,

in conjunction with the relevant research results (Mei et al., 2022, 2025; Liu Q et al., 2022), a rural human settlement environment quality index system was constructed from the perspective of system collaboration, and the degrees of coordination and sustainable development of the human–nature relationship were scientifically measured.

The natural support dimension focuses on the ecological foundation and resource carrying capacity, and core indicators such as natural disaster risk, vegetation coverage level, and water resource security level are selected to reflect the stability and sustainable supply capacity of rural ecosystems. These factors directly affect the agricultural production mode and spatial layout of villages, are related to the ecological security and sustainability of residents' lives, and are material prerequisites for the harmonious coexistence of man and nature. The economic development dimension focuses on growth momentum and structural optimization and encompasses the supporting role of the economic system in the improvement of the rural environment and its development quality through indicators such as density of commercial facilities, degree of industrial economic development, and the optimization of infrastructure. Economic development strategy must account for the impact of the growth scale, resource constraints and ecological influences; thus, the design of indicators should include the quality and sustainability of development. The social regulation dimension reflects the functions of institutional guarantees and cultural guidance, and indicators such as the coverage rates of public transport station and medical public services, the efficiency of rural governance, and coverage of public green space and leisure space are selected to characterize the coordinated role of the social system in resource

allocation, the establishment of behavioral norms and environmental governance. This system promotes the dynamic balance between environmental conservation and economic development through coordination and guarantee functions, which is a key link in realizing system coupling.

The index system constructed in this study is based on the logical framework of “natural support, economic drive, and social regulation”, forming a clear hierarchical and intrinsically related evaluation system. This system can be used to not only systematically describe the background of the rural ecological environment, economic development momentum and social governance ability but also reveal the interaction relationships and overall coordination levels among the three subsystems from the perspective of coupling and provide a systematic analysis framework for subsequent empirical research.

Table 1 Evaluation index system of rural human settlements

Target layer	Criterion layer	Indicator layer			Abbreviation	Weight	
The quality of the rural living environment	Natural environment	Slope Factor			SF	α_i	0.168
		Relief Degree of the Land Surface, RDLS	Degree of the Land Surface, RDLS	RDLS	β_i	0.177	
		Typhoon Exposure Frequency			ETEF	γ_i	0.165
		Geological Hazard Susceptibility		GHS	δ_i	0.135	

Economic environment	Normalized Difference		NDVI	π_i	0.196
	Vegetation Index				
			NDWI	θ_i	0.159
	Normalized Difference Water				
	Index				
			ELFD	α_t	0.185
	Express Logistics Facility				
	Density				
	Accessibility	to	AAM	β_t	0.183
	Agromarketplaces				
Social environment	Density of Retail and		DRCF	γ_t	0.098
	Convenience Facilities				
	Coverage Rate of Small Retail		CRSO	δ_t	0.171
	Outlets				
	Accessibility to Catering		ACF	π_t	0.185
	Facilities				
	Level of Industrial Economic		LIED	θ_t	0.178
	Development				
	Density of Automotive Service		DASF	α_j	0.209
	Facilities				
	Public Transport Accessibility		PTAI	β_j	0.191
	Index				

Provision Rate of Green and Recreational Spaces	PRGRS	γ_j	0.161
Coverage of Basic Medical Services	CBMS	δ_j	0.126
Availability of Waste Sorting Infrastructure	AWSI	π_j	0.186
Accessibility to Local Administrative Service Centers	ALAS	θ_j	0.127

3.2 Data sources

In this study, multidimensional data covering ecological conditions, economic activities and public services in the three studied subsystems, namely, the natural environment, economic environment and social environment, are collected. The data are derived mainly from remote sensing images, geospatial datasets and point-of-interest (POI) information. With the help of Python scripts and the ArcGIS Pro platform, data collection, raster division, coordinate unification, index standardization, and spatial density analysis were completed, and a multisource dataset with unified accuracy and spatial scale was constructed to provide reliable data support and a basis for the subsequent systematic evaluation of rural human settlements.

Table 2 Data sources

Serial number	Data type	Data sources	Handling method and description
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1	Digital elevation model (DEM)	Geospatial data cloud	For natural environment analysis (e.g. slope and topography)
2	Land cover information	Remotely sensed land use data in China over multiple periods (CNLUCC)	The distribution of rural residential land is extracted via remote sensing interpretation
3	NDVI and NDWI	Radio-corrected remote sensing images	The normalized vegetation index (NDVI) and water body index (NDWI) are extracted for ecological and water condition analysis
4	Point of interest (POI) data	Baidu Maps Open Platform	Focus on 12 types of POIs related to rural functions (such as infrastructure, public services, and commerce), and extract relevant indicators through classification statistics

3.3 Research methods

3.3.1 Kernel density function model

The kernel density function is a nonlinear estimation equation that is strongly robust and weakly dependent on the data distribution (Silverman); it is widely used in

studies of the agglomeration states of spatial regional distributions. The kernel density function value is positively correlated with the degree of aggregation of spatial variables. In this study, the spatial distribution and variability of the rural human settlement function were analyzed by using a kernel density function. The basic formula for the kernel density function is as follows:

$$f_N(X) = \frac{1}{Nh_N} \sum_{i=1}^N K\left(\frac{X_i - \bar{X}}{h_N}\right) \quad (1)$$

$$K(x) = \frac{e^{-0.5x^2}}{\sqrt{2}} \quad (2)$$

where is the kernel density estimation function of the random variable X; is the number of POIs representing different functions; is the kernel density of the variable; and is the kernel density, which is a positive number greater than 0, reflecting the estimation accuracy and is directly proportional to the smoothness of the kernel density curve $f_N(X)NK(x)Xh_N$.

3.3.2 Evaluation model of the quality of the rural living environment

The quality of rural human settlements is shaped by multiple factors, such as the ecological foundation, development conditions and public services, via a long-term dynamic interaction process. Most of the rural areas in Guangzhou are located on the edge of the city and are a combination of urban and rural areas, with complex natural conditions and significant uneven development. In this context, natural characteristics, economic activities and social services are systematically integrated via the following formulas:

$$NEQI = \alpha_i \times SF + \beta_i \times RDLS + \gamma_i \times NDVI + \delta_i \times NDWI + \pi_i \times TEF + \theta_i \times GHS \quad (3)$$

$$EEQI = \alpha_t \times ELFD + \beta_t \times AAM + \gamma_t \times DRCF + \delta_t \times CRSO + \pi_t \times ACF + \theta_t \times LIED \quad (4)$$

$$SEQI = \alpha_j \times PTAI + \beta_j \times PRGRS + \gamma_j \times CBMS + \delta_j \times AWSI + \pi_j \times DASF + \theta_j \times ALAS \quad (5)$$

$$REQI = \alpha \times NEQI + \beta \times EEQI + \varphi \times SEQI \quad (6)$$

where (3)–(5) are the natural environment quality evaluation function, economic environment quality evaluation function and social environment quality evaluation function, respectively. $\alpha_x, \beta_x, \gamma_x, \delta_x, \pi_x$, and θ_x are the weights of the indicators (see Table 3). $x = [i, t, j]$ (4) is the comprehensive evaluation function, which encompasses the environmental quality index of rural human settlements and the weights of the natural environment quality index, the economic environment quality index and the social environment quality index, with weight values of 0.337, 0.324 and 0.339, respectively. By integrating the three subsystems of nature, economy and society, a multifactor weighted model is constructed to systematically calculate the overall level and spatial differences of rural human settlements: α and β and φ

Table 3 Weights of factors by system

Project		Weight Allocation				
Index	α_i	β_i	γ_i	δ_i	π_i	θ_i
Weight	0.168	0.177	0.165	0.135	0.196	0.159
Index	α_t	β_t	γ_t	δ_t	π_t	θ_t
Weight	0.185	0.183	0.098	0.171	0.185	0.178

Index	α_j	β_j	γ_j	δ_j	π_j	θ_t
Weight	0.209	0.191	0.161	0.126	0.186	0.127

The rural residential environmental quality index (REQI) is used to characterize the performance of the “natural-economic-social” environmental system in rural areas. The index is calculated by standardization and weighting, and its value range is between 0 and 1, reflecting the overall quality of the living environment in a research unit. The closer the index value is to 1, the greater the synergy among the regional ecological environment, economic development and social services and the better the quality of the rural living environment. The closer the index value is to 0, the lower the system operation efficiency and the greater the imbalance in the levels of environmental, economic and social development.

Table 4 Classification of human settlement quality levels

Serial number	Interval	Composite index grade	Comprehensive characteristics
1	[0, 0.2]	Level 1	Excellent ecology, strong economy, and complete services
2	(0.2, 0.4]	Level 2	Coordinated development and optimal facilities
3	(0.4, 0.6]	Level 3	Balanced development needs to be improved

4	(0.6, 0.8]	Level 4	Weak foundation and insufficient services
5	(0.8, 1]	Level 5	Ecological fragility and lagging development

3.3.3 Coupled coordination degree model

To comprehensively examine the development and coordination levels of the natural, economic and social environments in a rural living environment and avoid the “illusion” of limited coordination for a certain system, a coordination degree model (CCDM) of the quality of rural human settlements in Guangzhou is constructed based on a quantitative analysis of the indicators of the natural environment, economic environment and social environment, drawing on the research of relevant scholars [66](Wang Shujia et al.). Additionally, the coordination level of rural human settlements is evaluated. The details are as follows:

$$C = \sqrt{1 - \frac{\sum_{i>j,j=1}^n \sqrt{(U_i - U_j)^2}}{\sum_{m=1}^{n-1} m}} \times \prod_{i=1}^n \frac{U_i^{\frac{1}{n-1}}}{\max U_i} \quad (7)$$

$$T = \sum_{i=1}^n \alpha_i \times U_i, \quad \sum_{i=1}^n \alpha_i = 1 \quad (8)$$

$$D = \sqrt{C \times T} \quad (9)$$

In Equations (7)–(8), when $n = 2$, C is the degree of coupling among the

“natural environment–economic environment”, “economic environment–social environment” and “natural environment–social environment”. When $n=3$, the degree of comprehensive coupling C for “the natural–economic–social environment” refers to the overall coordination level among subsystems, which is used to measure the contribution of the system to the degree of coordination. is the coefficient to be determined (Table 3.3.2). is the degree of coupling coordination of the three systems. Among them, $T\alpha_i DU_i \in [0, 1]$, where $C \in [0, 1]$. When the subsystems are relatively discrete, the C value is low; otherwise, *the* C value is higher. *According to the formula*, the higher the C value is, the closer the output of the function is to 1, and the higher the degree of coupled coordination of the interactive subsystem, and vice versa. On the basis of previous studies, we divide the degrees of coupling and coordination of rural human settlements in China into five levels (Table 5).

Table 5 Subsystem weights in the coupled coordination model

Coupling objects		Subsystem (weight)	
Natural environment - economic environment	Natural environment	Economic environment	
		0.506	0.494
Natural environment - economic environment	Natural environment	Economic environment	
		0.504	0.496
Economic environment - social environment	Economic environment	social environment	

	0.500	0.500
"Natural-Economic-Social" system	Natural environment 0.433	Economic environment 0.281
		social environment 0.286

Table 6 Classification of coupled coordination degrees

Serial number	Interval	Degree of coupling	Coupled coordination level
1	$0 < D \leq 0.2$	Low-level coupling	Severe imbalance
2	$0.2 < D \leq 0.4$	Antagonism	Moderate imbalance
3	$0.4 < D \leq 0.6$	Basic coordination	Barely coordinated
4	$0.6 < D \leq 0.8$	Run-in	Intermediate coordination
5	$0.8 < D \leq 1$	High-level coupling	High coordination

3.3.4 The quality of rural human settlements and its coupling coordination relationship

On the basis of the degree of coupled coordination (D) of the REQI and the “nature-economy-society” system, a bivariate spatial analysis model was constructed to reveal the comprehensive state of the rural human settlement environment system and the corresponding internal relationships. The REQI reflects the comprehensive

environmental, economic development and social conditions in rural areas, and D is used to measure the interaction and coordination between subsystems. The value range of both is 0 to 1, and numerical changes are continuous and correlated.

In the process of analysis, each research unit is located in the two-dimensional coordinate system, with the REQI on the vertical axis and D on the horizontal axis. The color scales with different depths in the figure represent comprehensive performance based on the levels of quality and coordination, and gradient changes reflect the overall trend of the system coupling relationship. The shallow area corresponds to the ideal combination of system operation states, whereas the deep area represents the relative weakening of system coordination and comprehensive quality. Through the analysis of different blocks in the matrix, the relative position and evolution direction of each research unit in the human settlement system can be identified.

This two-dimensional spatial analysis method helps reveal the comprehensive characteristics and system coordination levels of rural human settlements from a holistic perspective. Through the joint distribution analysis of the REQI and D, the matching relationship between the quality level and the coordination state can be investigated, which provides a quantitative and scientific basis for subsequent spatial partitioning and classification regulation.

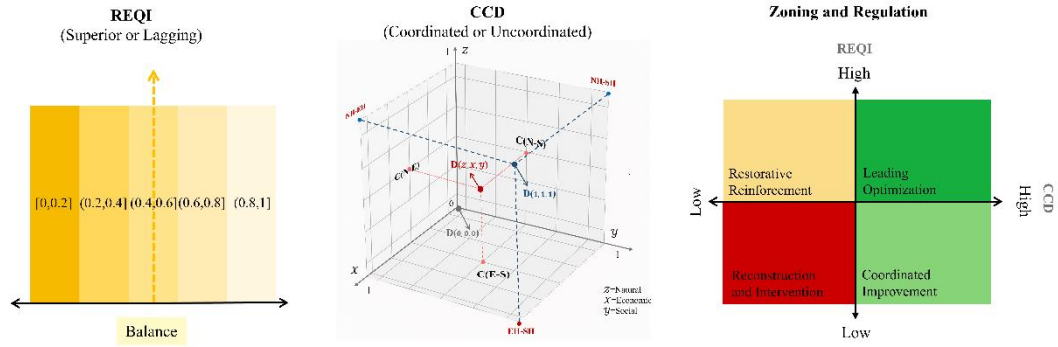


Fig. 2 Relationships between the comprehensive quality and coupled coordination levels of rural human settlements

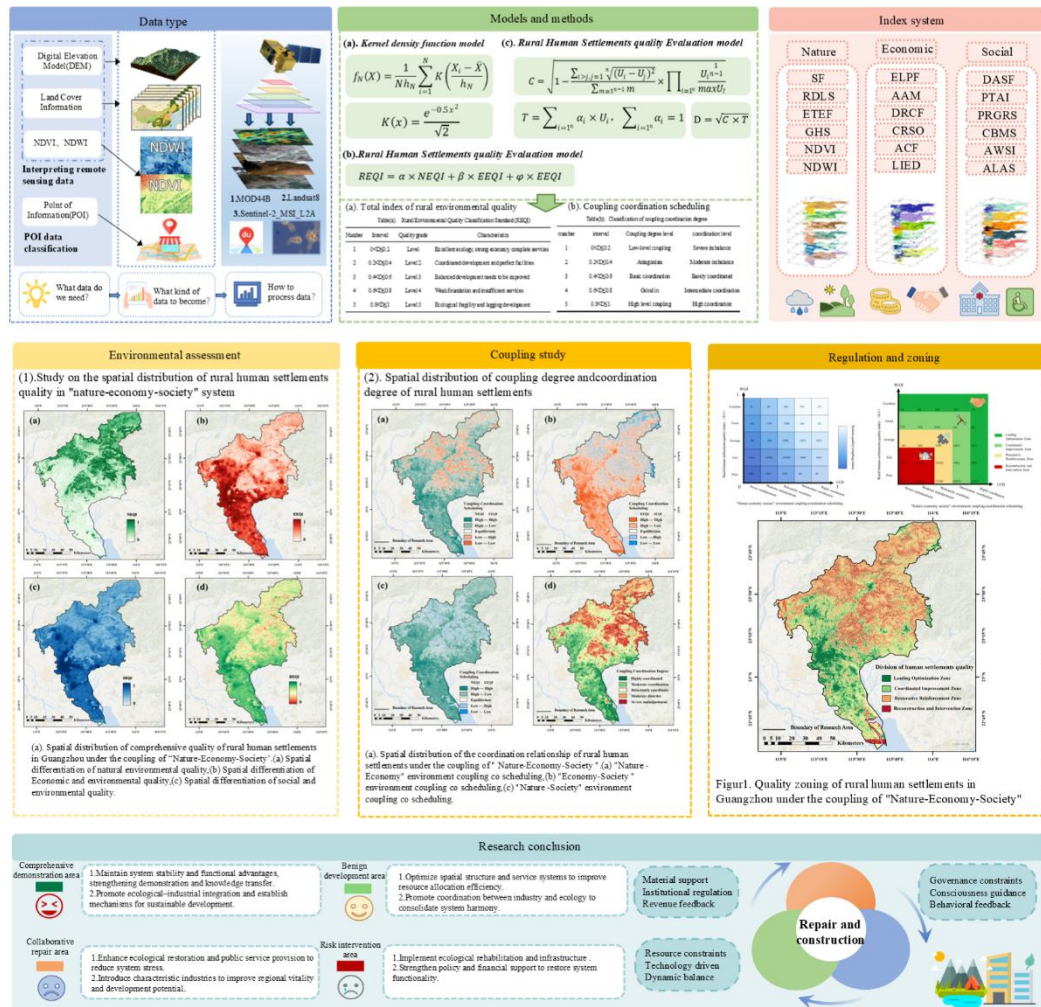


Fig. 3 Technological roadmap

3.4 Study area

Guangzhou (23°06'N-23°46'N, 112°57'E-114°03'E) is located in the core area of

the Pearl River Delta, with a total area of approximately 7434.4 km². As a national central city and the capital of Guangdong Province, Guangzhou was among the first regions in China to experience industrialization and urbanization. Its rural areas are distributed mainly on the periphery of the city, with a close relationship between resource flows and functional complementarity in the central urban area. The topography of Guangzhou reflects the spatial differentiation of Nanping and Beiqiu, with plains and river networks in the south and hills and low mountains in the north. In terms of the economy and society, the region has a high level of development and frequent urban–rural interactions. The urban spillover effect continues to promote the extension of infrastructure, public services and industrial resources to rural areas, gradually forming a typical urban–rural transitional living environment pattern. However, owing to multiple factors, such as ecological pressure, topographic differences and social structure adjustment, the rural living environment in Guangzhou is characterized by significant spatial heterogeneity, and the local natural, economic and social systems have complex multidimensional coupling characteristics.

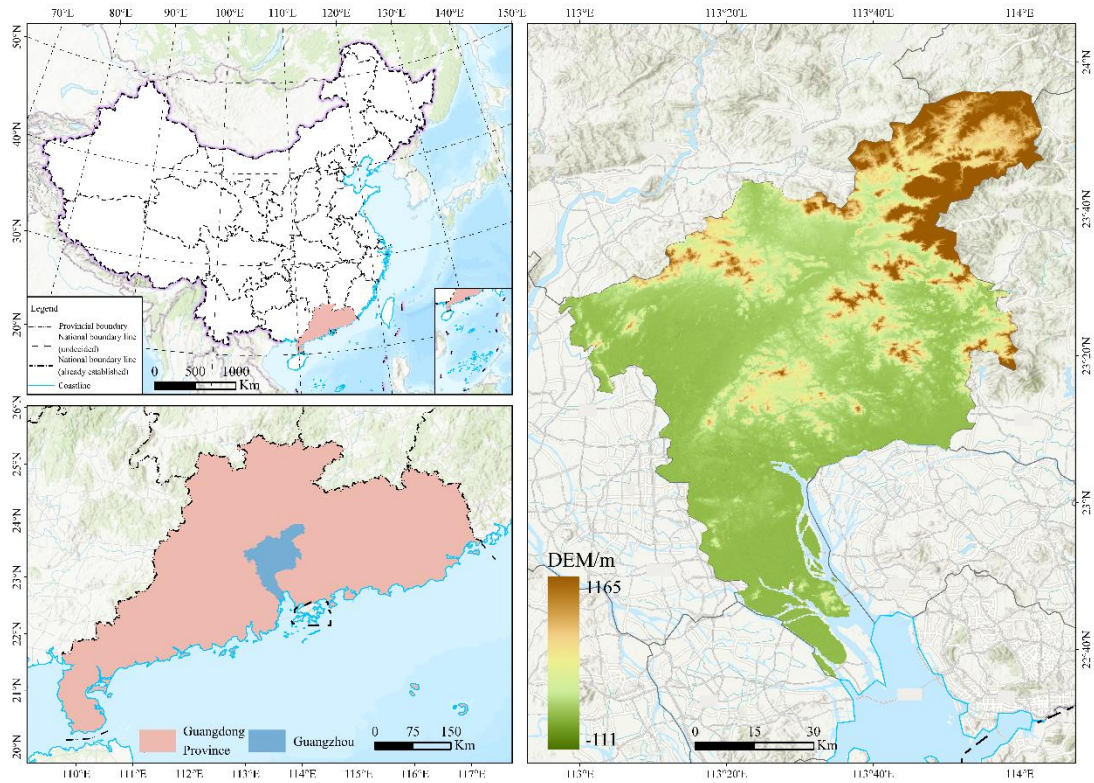


Fig. 4 Study area

4 Analysis of results

4.1 Spatial characteristics of the quality of the rural living environment

The quality of rural human settlements shows obvious spatial differentiation and interaction characteristics in three dimensions: natural, economic and social. In terms of the natural environment, the quality generally presents spatial patterns of “the south is better than the north” and “the plains are better than the hills” (Fig. 5.a). The southern and central regions are characterized by strong ecological carrying capacity, with flat terrain, developed water systems and high vegetation coverage, constituting an advantageous area for natural resources. The hilly and low-lying areas in the north and northwest have relatively poor natural resources due to the notable terrain undulations, high risk of geological disasters, and relatively weak ecological foundations, forming

low-quality areas. This ecological pattern is related to the spatial distribution of the industrial structure and transportation system, which exacerbates the economic development differences among regions (Figure 4.b). The periphery and node areas distributed along the main transportation corridors and economic axes are associated with dense economic activities and complete service facilities, reflecting the characteristics of belt agglomeration and forming the core area of the economic environment. The marginal and mountainous areas with inconvenient transportation and insufficient industrial support show an obvious quality gradient trend. The spatial distribution of social environment quality is uneven, mainly manifested in the spatial agglomeration differences between infrastructure and public service resources (Fig. 4.c). Plains and convenient transportation areas have formed a continuous service function agglomeration belt, with high levels of living convenience and social activity. Remote areas show a spatial pattern of "central agglomeration and peripheral attenuation" due to poor service networks and insufficient infrastructure coverage.

In general, the natural, economic and social environments in rural areas display significant unbalanced and interactive correlations in space. The natural environment lays the foundation for ecological construction and resource provision, the economic environment shapes the drivers and structure of regional development, and the social environment reflects the distribution differences between public services and quality of life. There is a synergistic effect between the three, and practical problems such as poor transformation and functional misalignment are prevalent. This spatial differentiation essentially reflects the complex interaction process of rural human settlements based

on the framework of the human-nature relationship: natural conditions constitute basic constraints, economic development drives spatial restructuring, and social systems are regulated through institutions and public services. Due to the lack of coordination among various dimensions, rural space is structurally characterized by "ineffective transformation of ecological advantages, imbalance between economic growth and environmental capacity, and uneven coverage of social services". Thus, a stable and efficient synergy mechanism has not yet formed for the rural living environment system in Guangzhou, and the overall spatial optimization of the area has considerable potential for improvement.

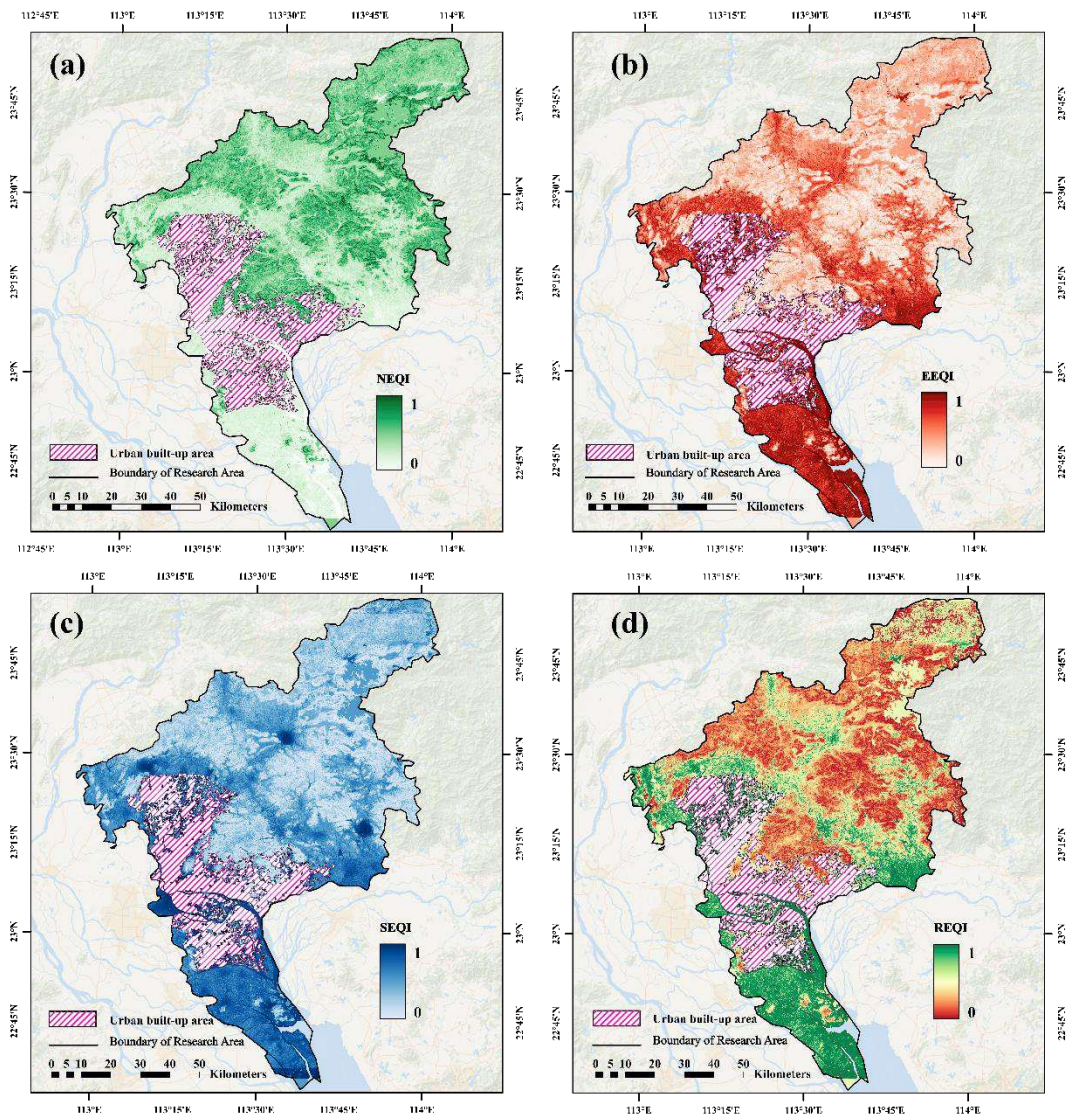


Fig. 5 Spatial distribution of the comprehensive quality of rural human settlements in Guangzhou under "nature-economy-society" coupling. (a). Spatial distribution map of environmental quality (b). Spatial distribution map of economic quality (c). Spatial distribution map of social quality (d). Spatial distribution map of the comprehensive quality of rural human settlements in Guangzhou

4.2 Spatial characteristics of the three-dimensional coupling of "nature-economy-society"

The results of the two-factor coupled coordination model show that the three types of subsystems display significant differentiation and strong regional correlations in

space, and the overall trends are characterized by complex and compound spatial patterns. The coupling relationship between the natural environment and the economy is mainly dominated by the ecological layout (Fig. 6.a), and high-value areas are mostly distributed in the southern region of the study area, with flat terrain, superior resource conditions and a good industrial foundation; thus, the area has a strong ecological carrying capacity and provides effective support for economic development. However, the northern and hilly areas are constrained by both topographic changes and lagging economic development, and the coupling level is generally low there. The coupling relationship between the natural environment and society is relatively weak as a whole (Fig. 6.c). The natural resource endowment has not been fully transformed to improve the public service level, and there is a lagging social function in some ecologically advantageous areas, with typical bipolar distribution characteristics of "good natural resources–shortcomings in public services". The plains area is characterized by strong system coordination due to the high degree of matching between ecological conditions and public facilities. In contrast, the economic and social environments are closely coupled (Figure 6.b). The core area forms a continuous agglomeration zone along the main transportation lines and economic belts, which reflects the spatial logic of "functional symbiosis and synergy strengthening", indicating that economic development can effectively drive the improvement of the social service system. A few areas with relatively complete public services but low levels of economic activity display local functional dislocations, while most peripheral areas are still in states of economic and social disadvantage.

The coupled coordination degree of the system reflects the interaction efficiency and synergy level of "nature-economy-society", and its spatial distribution displays significant regional differences (Fig. 6.d). In general, the core urban area and the plains area have the highest degrees of coordination, and benign interactions among the natural capacity, industrial development and social services are prevalent, creating an advantageous area for coupling and coordinated development. Although the ecological conditions are good in this area, there are differences in the functional structures of the systems due to the constraints of transportation accessibility and insufficient social service support. The low-coordination zone is concentrated in the mountainous areas in the north and northeast, showing the imbalanced characteristic of "excellent natural conditions but a weak economic foundation", and the efficiency of system interactions is low.

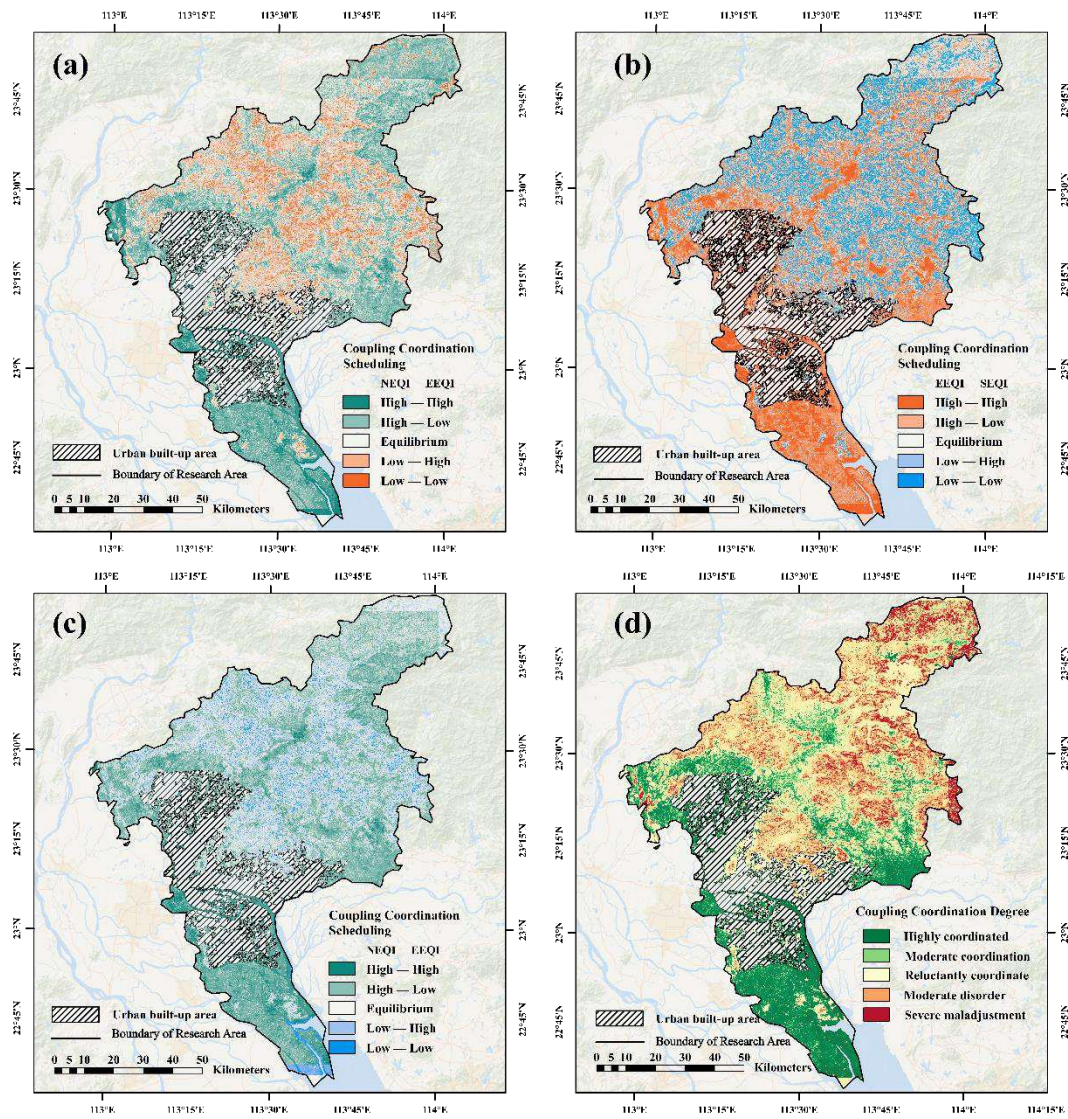


Fig. 6 Spatial distribution of the comprehensive quality of rural human settlements in Guangzhou under the coupling of "nature-economy-society". (a). Spatial distribution of comprehensive quality (b). Spatial differentiation of “Economy-Society” (c). Spatial differentiation of “Nature-Society” (d). Spatial distribution of the comprehensive quality of rural human settlements in Guangzhou under the coupling of “Nature-Economy-Society”

4.3 Zoning and regulation of the living environment

On the basis of the distribution characteristics of human settlement quality evaluation and coupled coordination, the rural living environment systems in the study

area can be divided into the following four types (see Fig. 7).

(1) Comprehensive leading optimization area. The system in these areas is characterized by high stability and mature development, and these should be the core areas of regional demonstration and experience promotion. These areas are distributed mainly in relatively flat areas in the southern and central parts of the study region, with strong transportation links. Notably, these areas are mostly clustered in patches or along corridors, accounting for 12.2% of the study area. Areas with high-quality human settlements usually have a stable resource base and strong social support capabilities. The natural system provides a resource-laden environment, the economic system operates efficiently, social management is relatively optimal, and the relationships among the three are relatively balanced, resulting in the formation of continuous positive feedback. Moreover, the spatial form is concentrated, transportation is convenient, residents' lives are comfortable, and resource utilization efficiency is high. The system in these areas has matured and has the ability to self-regulate and continuously optimize.

(2) Coordinated and improved cultivation areas. These areas have certain development potential, but the allocation of factors must be optimized, mainly around the comprehensive leading optimization areas and transition areas formed via outward expansion, accounting for 30.1% of the total study area. In most rural areas, the human settlement system is relatively coordinated but not yet stable. The driving force of economic development is strong, but there is a lag between ecosystem restoration and social system adaptability, which is manifested in the structural tension between

economic growth and ecological development. This characteristic reflects the dynamic process of “growth-constraint-rebalancing” in the rural system, which needs to be improved by increasing ecological compensation, promoting intensive land use and industrial restructuring, focusing on the reconfiguration and coordinated evolution of system elements, and gradually transitioning to a high-quality and highly coordinated steady-state pattern.

(3) Potential restoration and strengthening areas. The comprehensive functions in these areas need to be improved through systematic restoration and industrial integration. Notably, these areas are distributed mainly in the hilly mountains and peripheral areas from north to northeast, accounting for 39.2% of the total study area. The quality and coordination levels are medium to low, the living environment is strongly constrained by natural conditions, the economic vitality is insufficient, and the supply of social services is lagging. Most of these areas are located in hilly or urban–rural areas, with fragmented space, fragile ecology, and high dependence on resources. System coupling is manifested as “low-degree linkage–weak feedback–potential repair”, which involves gradually strengthening the positive interaction of the system and improving the regional self-organization ability through ecological restoration, facility improvement and green industry development.

(4) Focus on rebuilding intervention areas. The system operation in these areas is limited, and the degree of coordination is the lowest; thus, comprehensive rectification and policy support should be implemented. These areas are distributed mainly on the northern edge of the study area and in local mountainous areas, with a scattered mosaic

distribution, accounting for 18.5% of the total study area. Natural degradation, economic fragility and social lag have superimposed to form systematic constraints, reflecting the characteristics of “high ecological pressure, weak economic support, and a lack of social functions”. The system operation is in a low coupling state, and the feedback mechanism is not optimal. The reconstruction of the ecological security pattern should be the core focus, combined with policy support and the introduction of social capital, to promote ecological restoration, economic restructuring and social service optimization and realize system rebalancing and improved coupling.

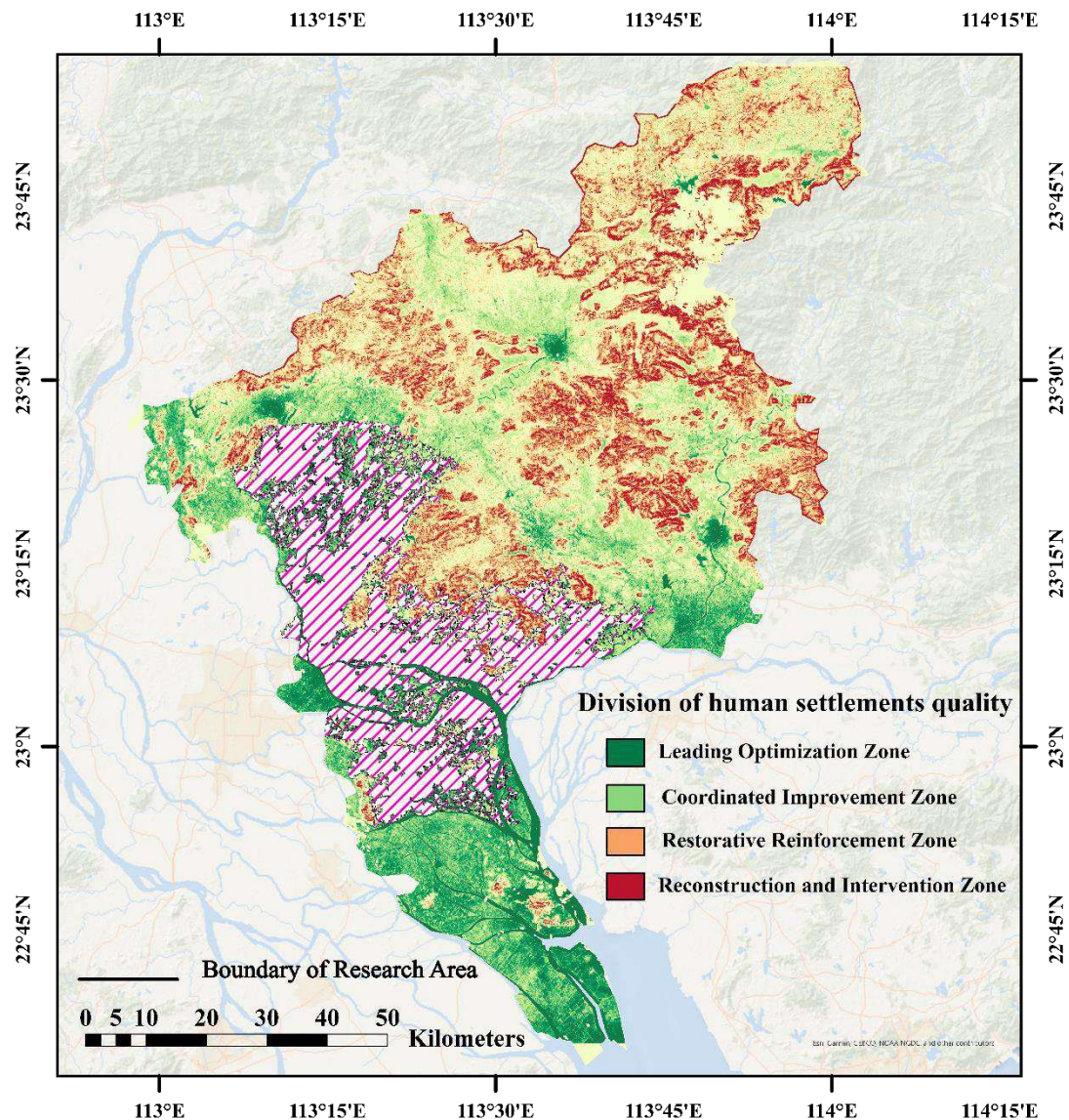


Fig. 7 Quality zoning of rural human settlements in Guangzhou under the coupling of
"nature-economy-society"

5 Conclusion and Discussion

5.1 Conclusion

In this study, a rural living environment quality evaluation framework covering three dimensions—natural, economic and social—is constructed, and the characteristics of the living environment and its coordination status in rural settlements in Guangzhou are systematically analyzed by combining rasterized data processing and a coupled coordination degree model. The main conclusions are as follows:

(1) The overall quality of rural human settlements in Guangzhou is at an upper middle level, but the spatial differentiation pattern is significant, with a decreasing gradient pattern. The quality of human settlements in the southern region, which has a superior natural environment and flat terrain, is high, whereas the northern mountainous area is affected by terrain restrictions and disaster risks, and the comprehensive index is low. The natural, economic and social subsystems show different degrees of differences and agglomeration in space, reflecting the complexity of the internal structure of the urban–rural transition zone.

(2) There is an obvious imbalance in the synergistic relationships among systems. The natural-economic systems are strongly coupled in some areas, and the ecological foundation provides certain support for the industrial layout. However, the overall degree of coupling between nature and society is weak, and ecological advantages have not been effectively transformed into public service efficiency. The economic–social

systems display a high level of coordination, indicating that economic development has a significant effect on the construction of public service networks. This unbalanced coupling between systems is a key bottleneck restricting the overall improvement of the regional living environment.

(3) Based on the comprehensive analysis of quality and coordination, various spatial development types, such as “high quality–high coordination”, “medium quality–low coordination” and “low quality–low coordination”, were identified, reflecting the different degrees of matching and dislocation between functional advantages and system interaction efficiency in each region. The rural living environment in Guangzhou has not yet formed a stable mechanism of balanced interaction and coordinated evolution among systems. This spatial structure not only reflects the varying pattern of human settlement quality but also highlights the dynamic differences in institutional supply, infrastructure, ecological capacity and industrial support among regions.

5.2 Discussion

Compared with previous studies that focused on a single system or a natural ecological evaluation, this paper provides a systematic deconstruction of the rural human settlement environment through multisource data fusion and spatial scale control, and a coupled coordination degree model is introduced to strengthen the spatial identification of the interactions between systems and expand the interpretive dimension of human settlement research. In terms of regional selection, this paper focuses on the rural marginal zones in economically developed areas, thus providing a

new empirical supplement for understanding the interaction mechanism of “urban spillover–rural response”.

The coupled analysis framework of “nature–economy–society” proposed in this study can be used to compensate for the lack of attention given to the system linkage mechanism in previous research on rural human settlements and provide a new perspective for studying human–nature relationships and regional coordinated development. At the practical level, the constructed multidimensional evaluation index system and coupled measurement method can provide methodological support for classification, governance and precise policy implementation in economically developed areas with rural spaces, especially for improving the environmental quality of human settlements and optimizing space use in urban-suburban integrated rural areas.

This study systematically explores the development of a theoretical framework and the application of this framework, but there are still certain limitations. On the one hand, the index system relies mainly on objective spatial data, which do not fully incorporate the subjective perception and behavioral characteristics of residents and may not fully reflect individuals’ initiative in terms of environmental cognition and spatial response. On the other hand, although the case area is limited to Guangzhou, a representative area, the extrapolation of the conclusions and the generalizability of the model must be further verified. Future research can combine resident surveys and social perception data to construct an “objective–subjective” two-way verification system and expand it to rural settlements in different types of regions to enhance the comparability and adaptability of the research. In addition, if the proposed framework can be

combined with local policy and governance mechanisms, it will further deepen the understanding of the formation mechanism of differences in the environments of rural human settlements and provide a more targeted theoretical basis for spatial governance.

Glossary

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