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Measurement of Urban-rural Integration Level and Spatial Pattern in the Core Area of Wuhan Metropolitan Area

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Abstract Urban-rural integration is the key to breaking the urban-rural dual structure and achieving coordinated regional development. Taking the core area of Wuhan metropolitan area (Wuhan – Ezhou – Huanggang – Huangshi, Wu – E – Huang – Huang) as the research object, this paper breaks through the limitations of the traditional administrative division scale, adopts a 1 km × 1 km high-resolution grid as the basic unit, and constructs an urban-rural integration evaluation system covering five dimensions: population, economy, society, space and ecology. Using multi-source spatiotemporal data [including LandScan, nighttime light, Point of Interest (POI), *etc.*], this paper measures the level of urban-rural integration through the combination weighting method, and explores its spatial pattern by using spatial autocorrelation and hotspot-coldspot analysis. The results show that the urban-rural integration in the study area presents an obvious composite structure of "one core leading, axis belts radiating, and multiple points linking". There is a significant positive spatial correlation (Moran's I index = 0.880 3) in the study area. A "high-high (H-H)" agglomeration area is formed with Wuhan urban area and its surrounding suburbs as the core, while the northern and southern wings (the Dabie Mountain and the Mufu Mountain areas) present "low-low (L-L)" agglomeration characteristics due to geographical barriers.

Key words Urban-rural integration; Wuhan metropolitan area; Spatial pattern; Spatial heterogeneity
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In the process of Chinese path to modernization, urban-rural integration has become the key path to break the urban-rural dual structure and achieve regional coordinated development[1], and also the core strategic direction of China's urban-rural relationship transformation in the new era[2]. Wuhan is the only mega city in central China and the core city of the Yangtze River Economic Belt. The core area of Wuhan metropolitan area (Wuhan – Ezhou – Huanggang – Huangshi, Wu – E – Huang – Huang) led by Wuhan is a strategic pivot for the development of the Yangtze River Economic Belt and a key engine for high-quality development in the central region. After the official approval of the *Wuhan Metropolitan Area Development Plan* in 2022, the region has become a forefront of national level metropolitan area urbanization and urban-rural integration practices[3]. However, the core area of Wuhan metropolitan area still faces significant development contradictions. There are obvious gaps in urban level and economic scale between Ezhou, Huangshi, Huanggang, and Wuhan, with significant regional stratification and spatial fragmentation characteristics. The two-way flow of urban and rural factors is not smooth, and the equalization of public services is insufficient, which seriously restricts the improvement of the quality and efficiency of urban-rural integration[4-6].

The measurement of urban-rural integration level and the analysis of driving mechanisms have always been the core issues in geography and regional economic research. Currently, relevant research has formed a rich theoretical accumulation and methodological system[7-9]. In terms of evaluation dimensions, the academic community has formed a multidimensional evaluation framework that includes economic, social, demographic, spatial, and ecological aspects[10-11]. In terms of measurement methods, entropy method[12], coupling coordination degree model[13-14], spatial autocorrelation analysis[15-16], *etc.* have become mainstream technical paths[17-18]. The research scale shows a gradual downward trend from national[19] and provincial regions to urban agglomerations[20-21] and county-level regions[22]. However, existing research still has significant limitations: the vast majority of studies use districts and counties as the smallest analysis unit, relying on traditional statistical yearbook data[23], which makes it difficult to characterize the micro gradient changes within the urban-rural continuum and accurately capture the spatial heterogeneity of the urban-rural transition zone[24], resulting in spatial differences among urban core areas, urban-rural transition zones, and suburban rural areas being masked by administrative averages[25]. At the same time, the specialized research on urban-rural integration focusing on urban agglomerations is relatively weak[26], and the integration and application of multi-source spatial data are insufficient, making it difficult to adapt to the development characteristics of urban agglomerations that cross administrative boundaries and have high-frequency factor flows[27].

Based on this, the core area of Wuhan metropolitan area is

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taken as the research object, which breaks through the scale limitations of traditional administrative units. Using a 1 km × 1 km refined grid as the basic research unit, a multidimensional urban-rural integration evaluation system is constructed, and the urban-rural integration level of the region in 2024 is measured. In this paper, the spatial autocorrelation is comprehensively used to characterize the spatial pattern of urban-rural integration. This paper fills the gap in existing research at a refined scale, accurately depicts the spatial differentiation law of urban-rural integration in the core area of Wuhan metropolitan area, and provides scientific support for optimizing spatial layout and implementing differentiated governance in the metropolitan area.

1 Measurement of urban-rural integration level and spatial pattern

1.1 Research design and unit scale selection In this paper, the core area of Wuhan metropolitan area (Wuhan – Ezhou – Huanggang – Huangshi, Wu – E – Huang – Huang) is taken as the research object. In order to avoid the interference of extreme high values in the main urban area within the third ring road of Wuhan on the measurement results, and eliminate the cover of "highland effect" on the spatial heterogeneity of urban-rural integration, the scope of the main urban area within the third ring road is removed, and it focuses on the core area of urban-rural transition and integrated development. This paper addressed the limitations of traditional county-level research by constructing a 1 km × 1 km refined grid as the basic research unit. Ultimately, the study area was divided into 33 115 effective grids, as shown in Fig. 1.

By gridding the research area, it is possible to eliminate the boundary effects caused by administrative divisions and accurately capture the continuous gradient changes in the urban-rural transition zone.

1.2 Construction of indicator system and data preprocessing Based on the evaluation system framework of five dimensions of urban-rural integration[28], eight indicators are selected from the five dimensions of population, economy, society, space, and ecology to construct an evaluation system for the level of urban-rural integration. Among them, the population integration dimension selects population density, the economic integration dimension selects nighttime light and economic vitality POI density, the social integration dimension selects education facility service level and medical facility service level, the spatial integration dimension selects weighted road network density, and the ecological integration dimension selects normalized difference vegetation index (NDVI) and scenic spot density. All indicators are positive, and the higher the value, the better the integration performance at corresponding dimension. The evaluation index system for urban-rural integration in the core area of Wuhan metropolitan area is shown in Table 1.

After the completion of the evaluation index system construction, due to the grid processing of multi-source data, it is easy to cause the values in urban areas to be too large and the grid values in rural areas to be too small, resulting in a right-handed skewed distribution of data. Therefore, a normality test and unbinding process are carried out on multi-source heterogeneous data. After testing, six original indicators all show severe right-handed skewed distribution. $\ln(x+1)$ logarithmic transformation is used to complete the unbinding process, and the raincloud plots before and after data transformation are obtained as shown in Fig. 2.

Verified by the raincloud plots, the transformed data are closer to a normal distribution, effectively reducing the influence of extreme values and amplifying the differences in the middle- and low-value regions. Moreover, the range standardization method is adopted to conduct dimensionless processing of all indicators, and the dimensional differences of different indicators are eliminated, laying the data foundation for subsequent indicator weighting and comprehensive measurement.

1.3 Spatial distribution pattern of urban-rural integration level In this paper, a linear combination of entropy method and analytic hierarchy process (AHP) is used for weighting. Setting subjective and objective weight coefficients of 0.5 each, the comprehensive weight of each indicator is calculated. Based on the combination weight, the comprehensive index of urban-rural integration for each grid unit is calculated. The natural breakpoint grading method is used to divide the integration level into five grades: level 1 (low level), level 2 (lower level), level 3 (medium level), level 4 (higher level), and level 5 (high level). The results are shown in Fig. 3, the urban-rural integration index in the core area of Wuhan metropolitan area.

The final identification shows a composite spatial pattern of "one core leading, axis belt radiating, and multi-point linkage" in the level of urban-rural integration in the research area. It combines the dual characteristics of decreasing circles and axial extension, and presents an overall differentiation trend of "single core leading, east – west axis linkage, and north – south wing lagging".

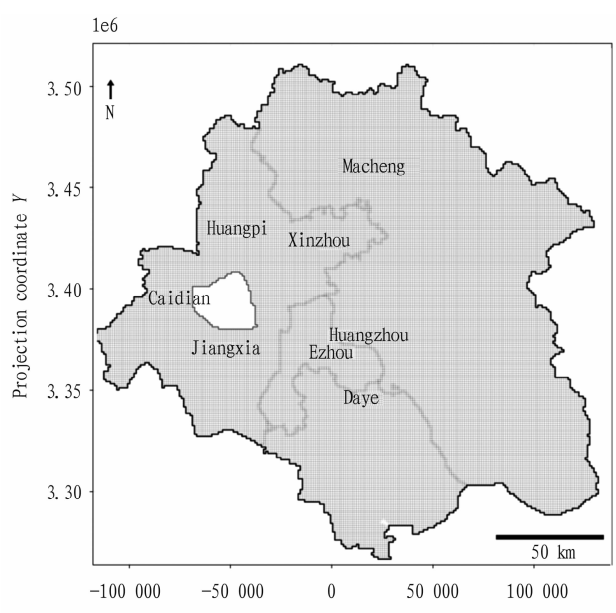


Fig. 1 Study area

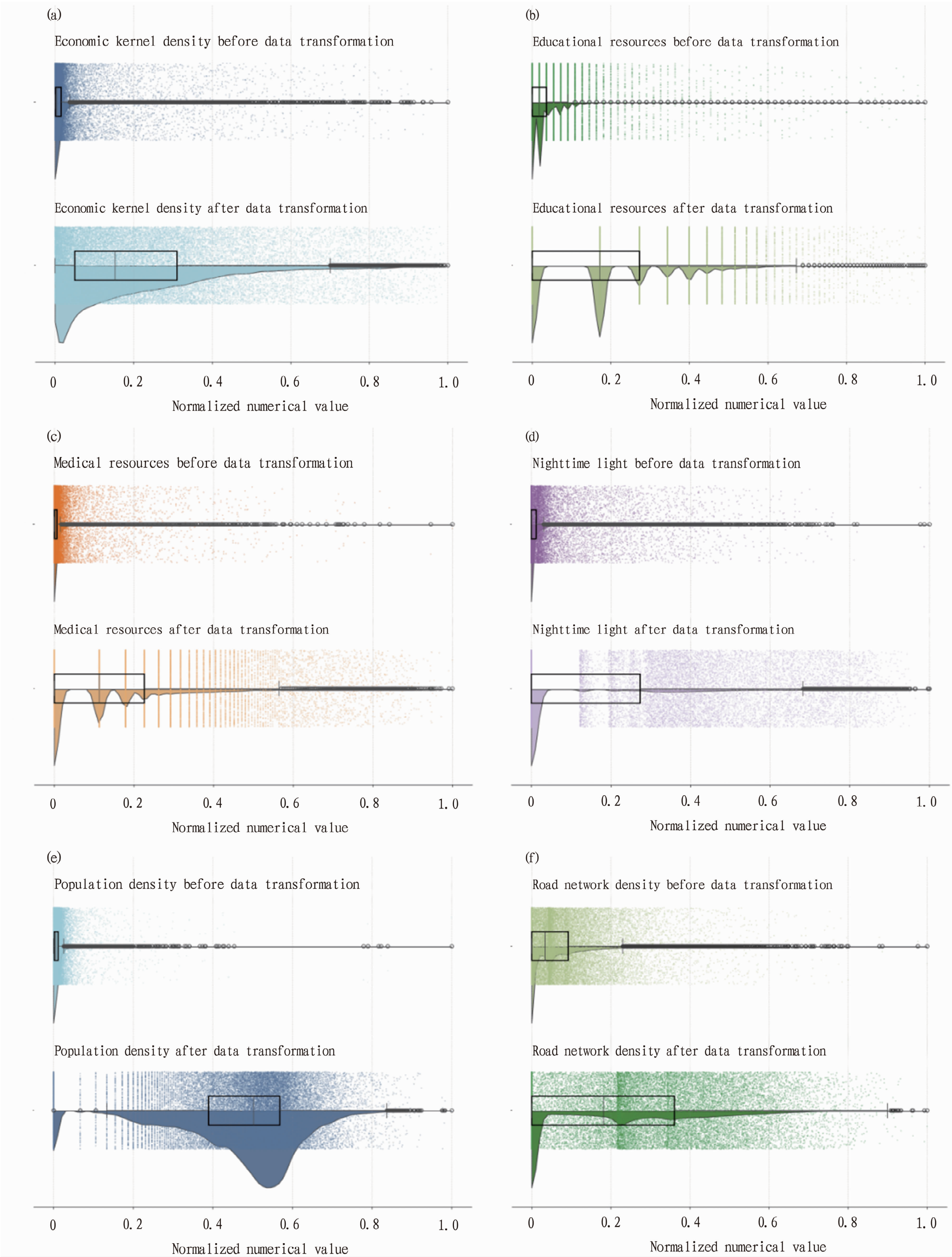
Table 1 Evaluation index system for urban-rural integration level in the core area of Wuhan metropolitan area

Criterion layer	Indicator layer	Indicator calculation method or data explanation	Indicator code	Indicator nature	Weight
Urban-rural population integration	Population density//persons/km^2	Population distribution raster data with 1 km of accuracy derived from the LandScan platform, resampling the data to the grid	X1	+	0.150 576
Urban-rural economic integration	Nighttime light index	Resampling nighttime light index to grid	X2	+	0.190 503
	POI density for accommodation, catering, shopping, corporate, financial insurance	After calculating the kernel density, assigning the values to each grid	X3	+	0.019 915
Urban-rural social integration	Walking to primary schools for 15 min	Number of times to cover each grid within a 1 000 m of buffer zone	X4	+	0.110 538
	Walking to middle schools and small cultural venues for 30 min	Number of times to cover each grid within a 2 000 m of buffer zone			
	Coverage rate of large cultural venues within 5 km	Number of times to cover each grid within a 5 000 m of buffer zone			
	Coverage rate of tertiary A hospitals within 8 km	Number of times to cover each grid within a 8 000 m of buffer zone	X5	+	0.129 432
	Coverage rate of comprehensive and specialized hospitals within 3 km	Number of times to cover each grid within a 3 000 m of buffer zone			
	Coverage rates of health centers and emergency centers within a 20 min walk	Number of times to cover each grid within a 1 500 m of buffer zone			
	Coverage rates of pharmacies and clinics within a 15 min walk	Number of times to cover each grid within a 1 000 m of buffer zone			
Urban-rural spatial integration	Road network density//km/km^2	Weighted length of road/grid area	X6	+	0.139 700
Urban-rural ecological integration	NDVI coverage rate	Resampling NDVI data with 250 m of precision to grid	X7	+	0.062 571
	Density of scenic spots (POI)	After calculating the kernel density, assigning the values to each grid cell	X8	+	0.118 371

The results show that the urban-rural integration pattern in the study area is evolving from a single center to multi center. The urban area of Wuhan is the core high-value area of the entire region, forming large-scale, high-density, high-level integrated contiguous patches, and demonstrating strong growth pole effects and factor aggregation capabilities. The central urban areas of counties and districts such as Echeng District, Huarong District, Huangzhou District, Xialu District, and Daye City have formed significant secondary centers, jointly building a development pattern of "one core and multiple support points" with the main core of Wuhan. The areas with high integration level have broken through administrative boundary restrictions, and contiguous distribution of crossing city has been achieved.

From the perspective of spatial diffusion characteristics, the level of integration shows a clear decreasing trend towards the periphery, with the Wuhan urban area and its secondary centers as the center. A complete "tight integration circle" is formed around the main city of Wuhan, which is a leading area for urban-rural integration. At the same time, the level of integration along the transportation and industrial axis of Wu – E – Huang – Huang shows a star shaped radiating trend, and the spillover effect of elements in the east – west development axis is significant. A continuous high-level integration zone is formed by Wuhan extending eastward to Ezhou, Huanggang and Huangshi, which confirms the spatial effectiveness of the integrated development of Wu – E – Huang – Huang.

From the perspective of regional differentiation, the spatial polarization characteristics of urban-rural integration level in the study area are prominent. High- and higher-level areas are concentrated in urban built-up areas and industrial development corridors, while mountainous counties at the southern foot of the Dabie Mountains in the north and the northern foot of the Mufu Mountains in the south are affected by geographical barriers and insufficient radiation from the central city, forming large-scale contiguous low-level fusion cold spots. Tuanfeng County, Xishui County and other areas are located in the transitional zone between high and low values. Although their current level of integration is in the medium range, they have the geographical advantage of undertaking the factor spillover of core area and are the core potential areas for urban-rural integration development in the study area.



Note: a. Economic kernel density; b. Educational resources; c. Medical resources; d. Nighttime light; e. Population density; f. Road network density.

Fig. 2 Raincloud plots comparing before and after data transformation

2 Clustering of urban-rural integration units

To accurately reveal the spatial dependence, clustering characteristics, and unit clustering patterns of urban-rural integration in the core area of Wuhan metropolitan area, using exploratory spatial data analysis (ESDA) method, spatial autocorrelation analysis is conducted from both global and local dimensions, completing the clustering identification and spatial pattern characterization of urban-rural integration units. Spatial autocorrelation analysis can measure the degree of spatial dependence of geographic element attribute values. Among them, global spatial autocorrelation is used to test whether there is an overall spatial clustering or dispersion trend in data attribute values across the entire domain, while local spatial autocorrelation is used to identify the clustering type of specific spatial units. The global Moran's I is the most commonly used metric for measuring spatial autocorrelation, and its calculation formula is:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_j - \bar{x})(x_j - \bar{x})}{S_0 \sum_{i=1}^{n}(x_i - \bar{x})^2}$$

where n is the number of spatial units; x_i and x_j are the level of urban-rural integration in regions i and j; $\bar{x}$ is the mean; $S_0 = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}$. The range of Moran's I values is $[-1, 1]$, where $I > 0$ represents positive spatial correlation (clustering of similar values), $I < 0$ represents negative spatial correlation (adjacent dissimilar values), and $I = 0$ represents random distribution. Local Moran's I is used to measure the degree of local spatial correlation between each spatial unit and its neighboring units, and its calculation formula is:

$$I_t = \frac{(x_i - \bar{x})}{S_i^2} \sum_{j=1}^{n} w_{ij}(x_j - \bar{x}), \quad S_i^2 = \frac{\sum_{j=1, j\neq 1}^{n}(x_j - \bar{x})^2}{n-1}$$

Through the significance test of local Moran's I, spatial units can be divided into four types of agglomeration: high-high agglomeration, which means that the level of urban-rural integration between this unit and neighboring units is high, forming hotspots; low-low agglomeration, which means that the level of urban-rural integration between this unit and neighboring units is low, forming a cold spot area; high-low agglomeration, where the level of the unit is high and the level of the neighborhood is low, forming a polarization zone; low-high agglomeration, refers to the formation of a transition zone where the unit level is low and the neighborhood level is high.

2.1 Global spatial clustering characteristics Based on the previously calculated level of urban-rural integration, the global Moran's I index for the level of urban-rural integration in the core area of Wuhan metropolitan area in 2024 is calculated.

The results showed that the global Moran's I index of urban-rural integration level in the study area reached 0.880 3, with a Z-score of 317.400 6 and a P-value of 0.001. It passed the significance test at the 1% of level, indicating that the level of urban-rural integration development in the core area of Wuhan metropolitan area presents a highly significant spatial positive correlation feature, and rejecting the null hypothesis of random distribution. This result indicates that areas with higher levels of urban-rural integration in the study area tend to be geographically contiguous, while areas with lower levels are relatively concentrated. There is a strong spatial spillover effect and synergistic effect in the development of urban-rural integration, which provides a statistical basis for conducting local unit clustering analysis.

A Moran scatter plot for the level of urban-rural integration development is drawn based on the local Moran's I index, as shown in Fig. 4.

The scatter plot shows that most of the observation points fall in the first and third quadrants, and are closely distributed around the regression line, showing a significant "H-H-L-L" distribution trend. The slope of the regression line ($I = 0.875\ 7$) further confirms the strong and significant spatial positive correlation of urban-rural integration in the study area. Among them, the H-H agglomeration areas represented by Xinzhou District, Huangshigang District, Xialu District, and Daye City constitute the regional development highland, showing significant contiguous characteristics and spatial spillover advantages. Luotian, Yingshan and other counties are located in the L-L agglomeration area, reflecting a significant "core – periphery" differentiation phenomenon in the level of urban-rural integration.

2.2 Local spatial clustering pattern To further implement the agglomeration characteristics to specific geographical units, a LISA map for the level of urban-rural integration development in the core area of Wuhan metropolitan area in 2024 is drawn based on grid scale, as shown in Fig. 5.

The results show that the research area as a whole presents a clear circular distribution pattern of "red in the middle, blue around the periphery, and gray in the transitional zone", with spatial positive correlation characteristics occupying an absolute dominant position. The H-H clustering area is concentrated in the suburban areas of Wuhan, as well as the adjacent Huarong and Echeng districts of Ezhou and Huangzhou district of Huanggang, and extends eastward to Daye City, forming a contiguous high-value agglomeration across urban areas, and confirming the spatial effectiveness of the integrated development of Wu – E – Huang – Huang. The L-L clustering area is widely distributed in the mountainous and hilly areas of the northern, northeastern, and southern parts of the metropolitan area, concentrated in peripheral counties such as Hong'an, Macheng, Luotian, Yingshan, and Yangxin, forming large-scale contiguous low-value clusters and exhibiting significant spatial lock-in effects. The extremely low spatial outliers of H-L and L-H types indicate that the level of urban-rural integration development in the study area has strong spatial continuity, and islanding effects rarely occur.

3 Conclusions and discussion

3.1 Conclusions This paper takes the core area of Wuhan metropolitan area as the research object, with a 1 km × 1 km refined grid as the basic research unit. By constructing a multidimensional urban-rural integration evaluation system, it accurately depicts the spatial differentiation law of urban-rural integration in this region in 2024. This study fills the gap in existing research at a refined scale, providing scientific support for optimizing spatial layout and implementing differentiated governance in urban areas. The main conclusions are as follows:

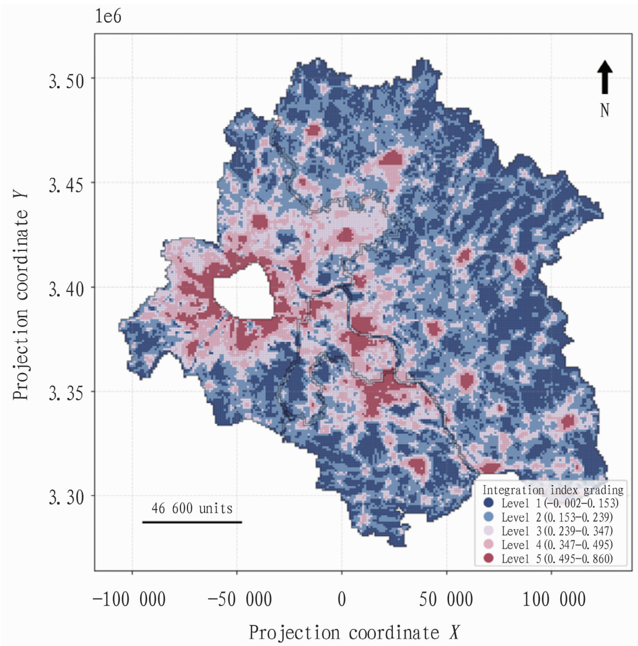


Fig. 3 Urban-rural integration index in the core area of Wuhan metropolitan area

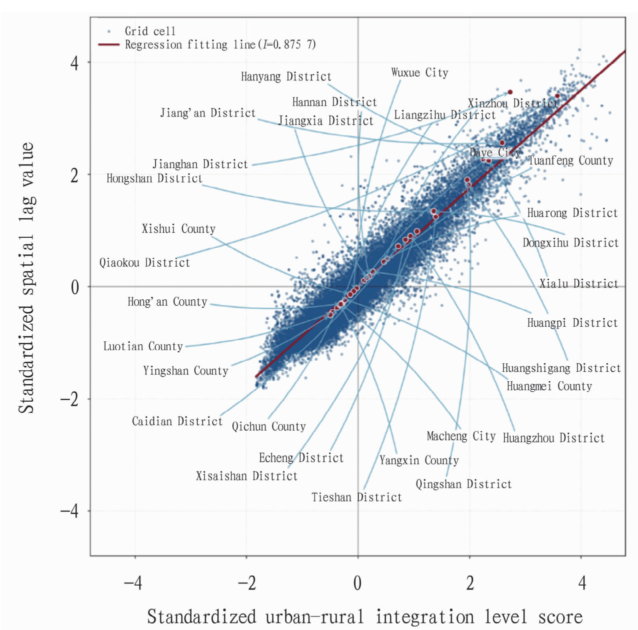


Fig. 4 Moran scatter plot of urban-rural integration development level

The spatial pattern of the core area of Wuhan metropolitan area presents a composite structure and gradient decreasing characteristics of "one core leading, axis radiating, and multi-point linkage". The measurement results show that the urban area of Wuhan exhibits a significant growth pole effect, driving the formation of a closely integrated circle in the suburban areas. The level of integration is not simply a circle expansion, but a star shaped radiating trend based on transportation corridors and industrial axes of Wu – E – Huang – Huang. There is a significant "center – edge" gradient effect within the region, and high-level fusion areas are concentrated in urban built-up areas, with fusion levels far exceeding those of the edge regions. The peripheral areas and natural barrier areas (such as the Dabie Mountains in the north and the Mufu Mountains in the south) are weakly influenced by radiation and still in a low-level fusion state, with prominent spatial polarization characteristics.

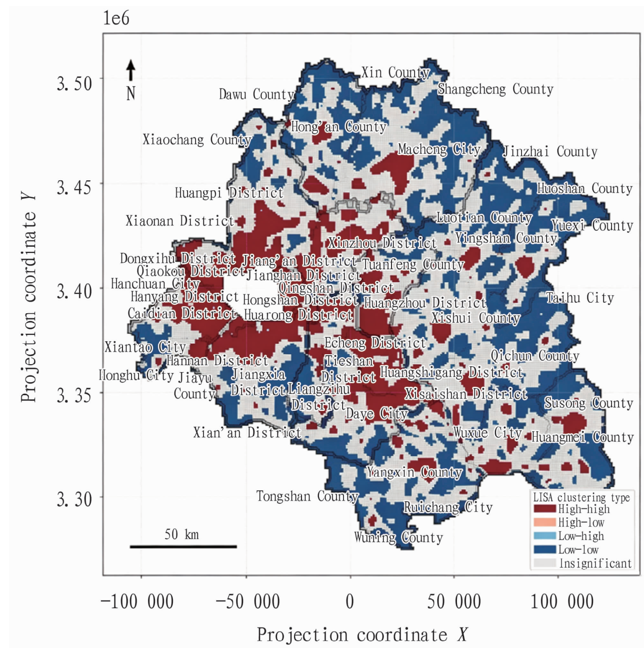


Fig. 5 LISA map of urban-rural integration level in the core area of Wuhan metropolitan area in 2024

3.2 Discussion Comparing this paper with previous research, it was found that traditional studies on urban-rural integration are limited by administrative unit statistical data and find it difficult to capture micro gradient changes within the urban-rural continuum. In this paper, multi-source grid data are introduced to achieve a methodological transition from "macro description of urban-rural gap" to "fine drawing of urban-rural connections", which can more finely identify transitional areas in the middle stage of integration and provide scientific prerequisites for accurate identification of integration depressions.

For the urban agglomeration, which is the most active area for urban-rural factor flow, industrial collaboration and infrastructure interconnection of crossing city have become the key to breaking administrative boundary restrictions. For example, the formation of the "Wu – E – Huang – Huang" contiguous high-value areas directly confirms the substantive effectiveness of regional integration strategies at the spatial level.

Although this paper has made some progress in measuring scale of urban-rural integration, there are still the following limitations. Firstly, the spatiotemporal limitation of data dimensions. In this paper, spatial static analysis is mainly conducted based on cross-sectional data in 2024, which fails to fully demonstrate the long-term dynamic evolution of urban-rural integration. In the future, multi temporal data can be introduced to explore the evolution laws of driving mechanisms. Secondly, the breadth of the indicator system needs to be expanded: due to the limitations of grid scale data acquisition, the current evaluation system focuses on hard indicators such as economy and infrastructure, and lacks measurement of "soft integration" dimensions such as psychological identity of urban and rural residents, cultural integration, and social governance. In the future, more comprehensive evaluation dimensions need to be constructed by combining more source data.

Overall, the research results provide a solid empirical basis for the policy-making of "one district, one policy" in the core area of Wuhan metropolitan area. In future planning, it is necessary to strengthen the spillover effect of the axis belt, rely on the multi center cluster development model to break the spatial lock of edge areas, and promote high-quality coordinated development of the region.

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