Proceedings of Business and Economic Studies, 2026, Volume 9, Issue 5
http://ojs.bbwpublisher.com/index.php/PBES
Online ISSN: 2209-265X
Print ISSN: 2209-2641

Study on the Evolution Characteristics of Regional Economic Spatial Pattern in Shandong Province: An Empirical Analysis Based on Nighttime Light Remote Sensing Data

Yuxia Wang[1]**, Yuhong Wang**[2]**, Qianqian Li**[1]**, Xuelian Wang**[1]

[1]Shandong Agriculture and Engineering University, Jinan 250100, China
[2]Jiaozhou Municipal Party Committee United Front Work Department, Jiaozhou 266300, China

Abstract: Based on the nighttime light data and relevant statistical data in Shandong Province from 2015 to 2024, this study integrates spatial pattern analysis and a modified economic gravity model to explore the evolutionary characteristics of the regional economic spatial pattern. The results show that county-level nighttime light presents a gradient distribution of "high in the core, low in the periphery", with the dual-core high-value areas of Jinan-Qingdao expanding continuously. In spatial distribution, regional economy shows a significant positive spatial correlation, while the degree of agglomeration weakens with fluctuations, reflecting a balancing trend of core radiation and peripheral catch-up. The standard deviational ellipse stretches northeast-southwest with an area expansion of 1.6%, indicating a gradual increase in spatial radiation capacity of the regional economy. The gravity center shifts from west-south to north-west, reflecting spatial expansion and partial adjustment of the economy. The total urban economic gravity has increased substantially, forming a development pattern dominated by Jinan-Qingdao and linked by sub-core circles such as southern Shandong. Radiation corridors of core cities have upgraded from local single points to full coverage, and corridor evolution is closely related to regional strategic development and transportation infrastructure. This study can provide a reference for optimizing the high-quality development strategy of regional economy in Shandong Province.

Keywords: Nighttime light remote sensing; Gravity model; Regional economy

Online publication: June 19, 2026

1. Introduction

With the in-depth implementation of the high-quality development strategy for the Yellow River Basin and the construction of the National Pilot Zone for Replacing Old Growth Drivers with New Ones, Shandong Province has gradually formed a spatial pattern with Jinan and Qingdao as dual cores, and coordinated development of Jiaodong, central Shandong and southern Shandong. However, practical problems such as the development gap between core and peripheral areas, differentiated vitality of county economies, and unbalanced efficiency of factor flow remain prominent, restricting the achievement of high-quality economic development goals [1].

Traditional regional economic research mostly relies on statistical data such as GDP and per capita income. Although they can reflect differences in economic aggregate, they have limitations such as inconsistent statistical calibers, lagged data updates, and difficulty in depicting spatial continuity [2,3]. The emergence of nighttime light remote sensing data provides a new solution to this problem. Nighttime light intensity has a significant positive correlation with regional economic activity intensity, and its advantages of spatial continuity and timeliness can effectively make up for the shortcomings of traditional statistical data, making it an ideal variable for measuring the intensity and distribution characteristics of economic activities [4,5].

Researchers have conducted a large number of relevant studies and confirmed that nighttime light data can be used to characterize regional economic development levels. For example, Chen Jin (2003) conducted a study on urbanization level based on nighttime light data and pointed out that the light index has a high correlation with the composite index reflecting urbanization level, which can be used for spatiotemporal differentiation and monitoring of urbanization [6]. Furthermore, Wei Kaiyan (2021) conducted a spatial simulation of GDP in Shanxi Province based on NPP-VIIRS nighttime light data and found a high correlation between nighttime light data and GDP, with accurate and reliable spatial simulation results of GDP [7]. At present, nighttime light data have been widely used in urbanization level measurement, regional economic difference assessment and other related fields [8,9].

As a classic tool for quantifying inter-regional economic connections, the economic gravity model can reveal the potential intensity of factor flow between cities through the coupling relationship of “economic quality-spatial distance” [10]. Traditional gravity models mostly use statistical data such as GDP and population to characterize “economic quality” and geographical distance to characterize “spatial accessibility”, but the negligence of spatial continuity of economic activities has led to certain deviations in depicting regional economic connections. Relevant researchers, such as Niu Zhensheng (2024), Zhang Zhuoyao (2025), et al., introduced the nighttime light index, which characterizes the balance of internal economic and social development of cities, into urban comprehensive development quality on the basis of existing gravity models, overcoming the drawbacks of strong subjectivity and poor interpretability in current urban quality index selection. This can more accurately measure the intensity of inter-regional economic interactions and support the analysis of the evolution of economic connections [11,12].

Based on the above research status and practical needs, this study takes 137 counties in Shandong Province as research objects, selects nighttime light data from 2015 to 2024 as the core data source, combines statistical data and spatial analysis technology to identify the evolution characteristics of county-level economic spatial pattern in Shandong Province, reveal the spatial agglomeration and diffusion laws of county economy, and quantify the intensity and evolution mechanism of economic connections between cities based on the modified economic gravity model. This study aims to fill the gap in long-term nighttime light and economic spatial pattern coupling research at the county scale in Shandong Province, and provide theoretical and practical references for optimizing the provincial regional economic layout and promoting the implementation of the “One Group, Two Cores, Three Circles” strategy.

2. Research methods

2.1. Data sources

The global 500-meter resolution “NPP-VIIRS-like” nighttime light dataset (2000–2024) used in this paper was developed by Chen Zuoqi and Yu Balang’s team and relies on the National Earth System Science Data Center (https://www.geodata.cn), with a spatial resolution of approximately 500 meters (15 arc seconds) and a coordinate system of GCS_WGS_1984. The data quality has been verified at multiple scales, can truly reflect the temporal changes of population and light brightness, and is suitable for urbanization monitoring, socio-economic assessment, environmental change research and other fields.

Socio-economic statistical data: The socio-economic statistical data used are compiled from the *Shandong Statistical Yearbook (2015–2025)* published by the Shandong Provincial Bureau of Statistics (http://tjj.shandong.gov.cn/col/col6279/index.html);

Administrative boundary data: In this paper, nighttime light values are partitioned, cropped and mapped for statistical analysis based on administrative boundary data, which are obtained from the National Geomatics Center of China (http://www.ngcc.cn).

2.2. Research methods

2.2.1. Spatial correlation analysis

Spatial autocorrelation is a core method for measuring the interdependence between observed values of spatial units and their neighboring units, which can reveal the agglomeration and dispersion characteristics of regional economic spatial patterns [13]. This paper takes 136 county-level units in Shandong Province as research objects, constructs a spatial weight matrix (adjacency weight or distance decay weight), and measures the spatial correlation model of regional economy through Moran’s I index [14]. The formula is as follows:

$$I_{GM} = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \cdot \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\left(X_i - \bar{X}\right)\left(X_j - \bar{X}\right)}{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2} \tag{1}$$

X_i and X_j are the nighttime light intensities of counties *i* and *j* (characterizing economic scale), n is the total number of counties, and $\bar{X}$ is the average light value. Moran’s I ranges from [-1, 1]: $I_{GM}>0$ indicates positive spatial correlation and economic agglomeration; $I_{GM}<0$ indicates negative spatial correlation and economic dispersion; $I_{GM}=0$ indicates spatial randomness.

2.2.2. Spatial pattern analysis

The Standard Deviational Ellipse (SDE) and gravity center model are core methods for revealing the spatial distribution characteristics of regional economy [14]. Among them, the standard deviational ellipse comprehensively characterizes the centrality, spread, directionality and morphological characteristics of geographical elements through three parameters: ellipse gravity center, azimuth and standard deviation of long and short axes [15]. This study combines the standard deviational ellipse and gravity center model to quantitatively describe the spatial expansion direction, dispersion degree and core area migration trajectory of regional economy in Shandong Province.

Gravity center coordinates:

$$X_c = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}, \quad Y_c = \frac{\sum_{i=1}^{n} w_i y_i}{\sum_{i=1}^{n} w_i} \tag{2}$$

Azimuth α characterizes the dominant direction of spatial distribution, and the calculation formula involves the covariance and variance combination of coordinate deviations.

$$\tan\alpha = \frac{\left(\sum_{i=1}^{n} w_i^2 \tilde{x}_i^2 - \sum_{i=1}^{n} w_i^2 \tilde{y}_i^2\right) + \sqrt{\left(\sum_{i=1}^{n} w_i^2 \tilde{x}_i^2 - \sum_{i=1}^{n} w_i^2 \tilde{y}_i^2\right)^2 + 4\sum_{i=1}^{n} w_i^2 \tilde{x}_i^2 \tilde{y}_i^2}}{2\sum_{i=1}^{n} w_i^2 \tilde{x}_i \tilde{y}_i} \tag{3}$$

The standard deviations of long and short axes (σx, σy) are calculated by coordinate rotation projection to quantify the range and morphological heterogeneity of spatial distribution.

$$\delta_x = \sqrt{\frac{\sum_{i=1}^{n}(w_i\tilde{x}_i \cos\alpha - w_i\tilde{y}_i \sin\alpha)^2}{\sum_{i=1}^{n} w_i^2}} \tag{4}$$

$$\delta_y = \sqrt{\frac{\sum_{i=1}^{n}(w_i\tilde{x}_i \sin\alpha - w_i\tilde{y}_i con\alpha)^2}{\sum_{i=1}^{n} w_i^2}} \tag{5}$$

(xi, yi) are the geometric center coordinates of county units; w_{ij} is the average nighttime light intensity of counties (characterizing economic scale weight); n is the number of counties; ($\tilde{x}_i$, $\tilde{y}_i$) are the coordinate deviations from the research object center to the gravity center.

2.2.3. Economic gravity model

The theoretical framework of the Regional Economic Gravity Model is derived from Newton's law of universal gravitation. By quantifying the economic "mass" and "distance" between cities, it measures the potential intensity of economic interaction. The basic form of the model is [16]:

$$R_{i,j} = K_{i,j}\frac{M_i M_j}{d_{i,j}^2} \tag{6}$$

Where $R_{i,j}$ is the economic gravity of city i to city j, reflecting the intensity of economic connection; $M_i and M_j$ are the economic masses of city i and city j, characterizing the comprehensive economic strength of cities; $d_{i,j}$ is the economic distance between city i and city j, reflecting the impact of spatial accessibility on economic connection; $K_{i,j}$ is the economic gravity coefficient, reflecting the relative new gravity of the direction of factor flow between cities.

To enhance the fit between the model and reality and improve the reliability and effectiveness of the model, refer to Yang Weizhong's (2019) relevant research to modify the parameters in **Equation (6)** to better reflect the economic relationship between cities [17]. The modified factors are: gravity coefficient $K_{i,j} = \frac{G_i}{G_i + G_j}$, reflecting the direction and degree of economic force between cities, where G_i and G_j are the GDP outputs of city i and city j respectively; total economic volume $M_i = \sqrt{P_i \cdot V_i}$, $M_j = \sqrt{P_j \cdot V_j}$, representing the total economic volume of city i and city j respectively, where P_i, P_j and V_i, V_j are the population and total urban nighttime light of city i and city j respectively; $d_{i,j} = D_{i,j}\left(1 + e^{-\sqrt{\rho_i \rho_j}}\right)$, $D_{i,j}$ is the shortest distance between city i and city j, ρ_i, ρ_j are the road densities of city i and city j.

3. Results and analysis

3.1. Nighttime light distribution characteristics

Nighttime light data can reflect the intensity and development level of regional economic activities to a certain extent. The higher the light value, the more active the economy usually is. The average nighttime light data of each county in Shandong Province from 2015 to 2024 are divided into five levels according to the same standard: high (>35), relatively high (25–35), medium (15–25), relatively low (5–15), and low (<5) (**Figure 1**). Overall, in 2015, the high-value nighttime light areas (>35) in Shandong Province were only scattered in the main urban areas of core cities such as Jinan and Qingdao, and most prefecture-level cities were mainly medium and low levels (<15); by 2018, the high-value light areas of Jinan Metropolitan Area and Qingdao Metropolitan Area began to spread to surrounding counties, and the light levels of regional central cities such as Yantai and Weifang entered the relatively high range (25–35); in 2021, the "core-periphery" gradient of light intensity was further strengthened, the proportion of counties with medium and above levels (≥15) in central Shandong and Jiaodong areas increased significantly, and the light levels of some counties in southwestern Shandong also rose from "low" to "relatively low"; in 2024, the high-value areas had formed contiguous distribution belts such as Jinan-Zibo and Qingdao-Weifang, the main urban areas and suburban counties of most prefecture-level cities were stably at relatively high and above levels, and only a few peripheral counties in northwest Shandong still maintained low levels (<5).

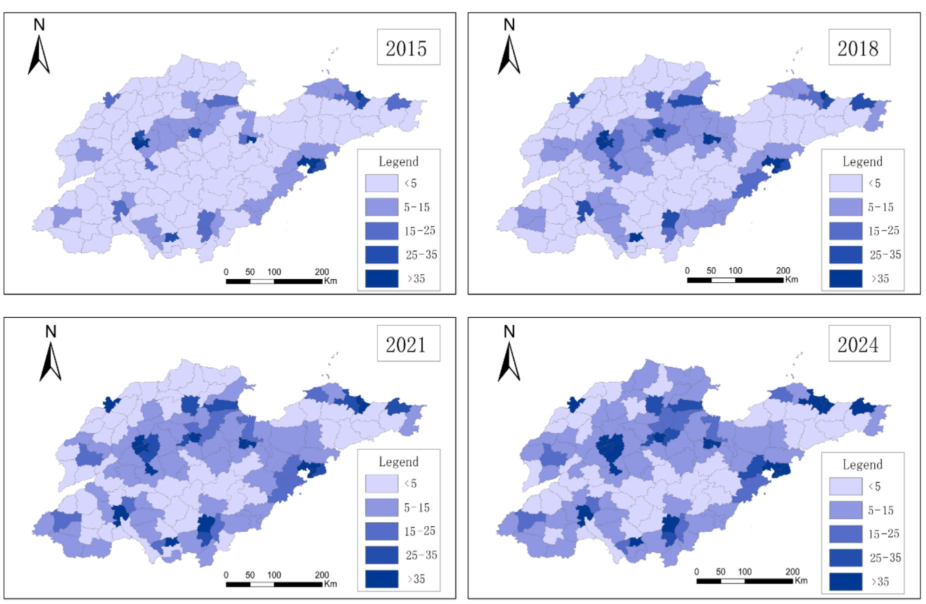

Figure 1. Grade distribution of average county nighttime light.

3.2. Analysis of regional economic development pattern

3.2.1. Spatial correlation

As shown in **Table 1**, the correlation index of county-level average nighttime light in Shandong Province from 2015 to 2024 is in the range of 0.51-0.61, and the *P*-value is at a high level, showing a significant positive spatial correlation. However, from the perspective of temporal evolution, the correlation index dropped to a stage low of 0.5182–0.5125 during 2021–2022. During this period, the proportion of "medium" level in central Shandong and Jiaodong areas increased significantly, the radiation effect of core cities was enhanced, and the original low-level counties gradually transitioned to medium level, breaking the previous strong agglomeration pattern of “high-value core, low-value periphery”, leading to a decline in spatial correlation; while the correlation index rebounded slightly in 2023–2024 (0.5418 in 2023), corresponding to the formation of “Jinan-Zibo, Qingdao-Weifang” contiguous belts in high-value areas, the agglomeration range of high-level counties expanded, and the positive spatial correlation was strengthened again.

Table 1. Spatial correlation of average county nighttime light

Year	Correlation	*P*-value	Year	Correlation	*P*-value
2015	0.6082	9.9694	2020	0.5486	8.7136
2016	0.6033	9.8768	2021	0.5182	8.2296
2017	0.5792	9.3771	2022	0.5125	8.1333
2018	0.5843	9.4632	2023	0.5418	8.6464
2019	0.5590	8.9482	2024	0.5262	8.3867

3.2.2. Spatial pattern evolution

This paper analyzes the evolution characteristics of regional economic spatial pattern in Shandong Province through the area change and gravity center movement of the standard deviational ellipse (**Figure 2**).

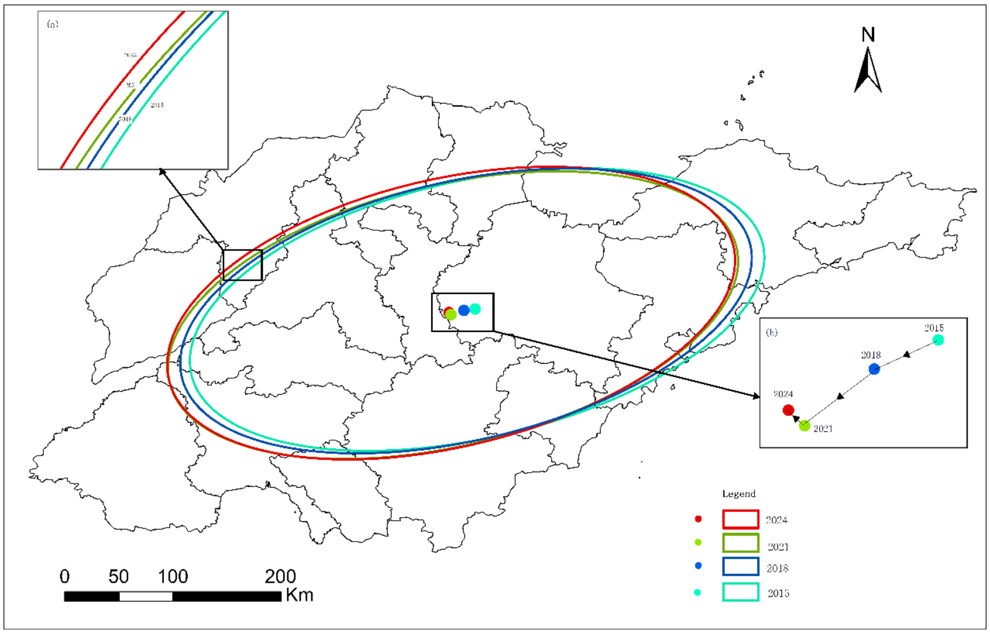

Figure 2. Standard deviational ellipse and gravity center movement of county nighttime light.

During the study period, the azimuth of the standard deviational ellipse remained stable at 50°–52°, indicating that the dominant extension direction of county economic space is mainly northeast-southwest, which is consistent with the economic gradient pattern of “Jiaodong Peninsula-Central Shandong-Southwest Shandong” in Shandong Province. In addition, the short axis, long axis and area of the ellipse all showed an increasing trend. The short axis increased from 12.53 km to 12.96 km, the long axis remained at about 20 km, and the area expanded from 81943.62 km² to 84276.65 km². This indicates that the spatial radiation capacity of county economy has gradually increased, and economic activities in core areas have spread to surrounding counties, promoting the expansion of the overall economic space (**Table 2**).

From the perspective of gravity center movement, from 2015 to 2021, the ellipse moved west-south (cumulative distance 18830 m), and the short and long axes expanded simultaneously, indicating that the economic space was dominated by "gradient diffusion". Economic activities in core areas (such as Jinan and Qingdao) spread to central and southwestern Shandong counties in the southwest, driving the improvement of economic activity in peripheral counties and enhancing the balance of economic space; from 2021 to 2024, the ellipse turned to move north-west (distance 2380 m), and the expansion speed of the short axis accelerated (the short axis increased by 0.3 km from 2021 to 2024, higher than 0.13 km from 2015 to 2021), reflecting the enhancement of economic agglomeration in local areas during this period, economic activities in northern counties of Jiaodong Peninsula agglomerated, forming new local economic cores, and promoting a small callback of the economic spatial gravity center to the northeast.

Table 2. Parameters of standard deviational ellipse

Year	Short Axis (Km)	Long Axis (Km)	Area (Km²)	Azimuth (°)	Gravity Center Movement Direction	Movement Distance (m)
2015	12.53	20.81	81943.62	52.01	0	0
2018	12.58	20.16	82066.55	51.44	West-south	8387
2021	12.66	20.78	82634.53	50.82	West-south	10443
2024	12.96	20.70	84276.65	50.35	North-west	2380

3.3. Urban economic gravity analysis

Based on the modified regional economic gravity model, the economic gravity values of each prefecture-level city in Shandong Province were calculated respectively, and the economic gravity grade map of each city was made according to the same standard (**Figure 3**).

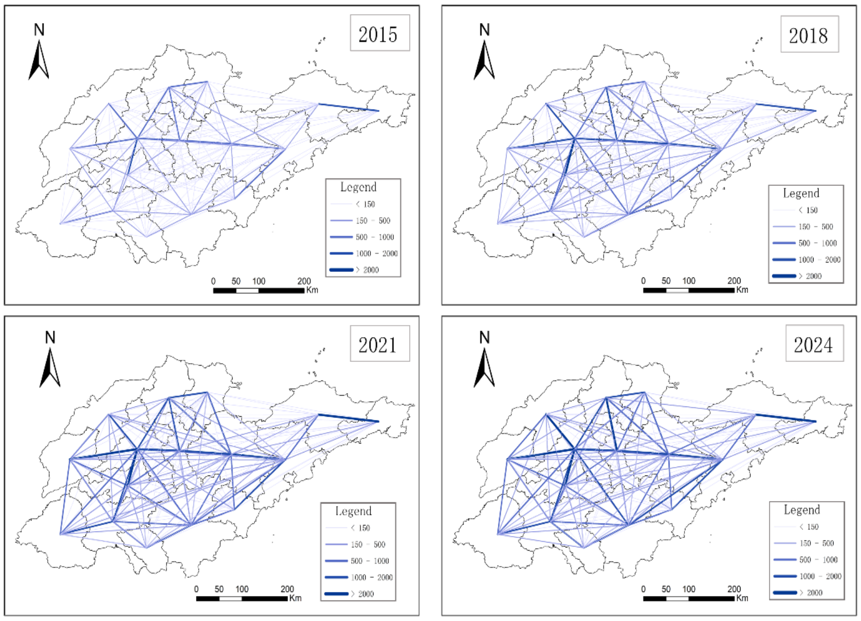

Figure 3. Grade distribution of urban economic gravity.

During the study period, the one-way radiation corridors of Jinan and Qingdao expanded from "local single points" to "full coverage", and the corridor direction was highly consistent with traffic arteries and population flow directions. Jinan's "cross radiation corridor": in 2015, only local corridors of "Jinan→Tai'an (south), Jinan→Zibo (east)" were formed (gravity values 1642 and 1097); by 2024, it expanded to a cross corridor of "Jinan→Tai'an (5928), Jinan→Liaocheng (2726), Jinan→Dezhou (2058), Jinan→Zibo (3722)", covering central Shandong, northwest Shandong and southwest Shandong; this evolution is directly related to the construction of Jinan-Liaocheng Expressway, Jinan-Tai'an Expressway and the development of Jinan National Pilot Zone for Replacing Old Growth Drivers with New Ones. Factors flow along traffic arteries, promoting the contiguous growth of one-way radiation values in the corridor. Qingdao's "coastal arc corridor": in 2015, only a single corridor of "Qingdao→Weifang (west)" was formed (gravity value 896), and by 2024, it expanded to a coastal arc corridor of "Qingdao→Weifang (2524), Qingdao→Yantai (995), Qingdao→Rizhao (1434)", covering Jiaodong Peninsula and southeast Shandong; this evolution is related to the construction of Qingdao SCO Demonstration Zone, and the coordination of port economy and export-oriented industries has promoted the formation of a "linked development belt" among coastal cities.

In addition, a regional linkage circle with sub-core cities as nodes has gradually formed, which can effectively connect core radiation and peripheral adsorption and build a global economic connection network. For example, the southern Shandong sub-circle (Linyi-Jining-Zaozhuang), in 2015, the one-way radiation values of Linyi to Zaozhuang and Jining to Heze were all lower than 600, but in 2024, they increased to 1369 and 1830 respectively; relying on the industrial transfer policy of the Southern Shandong Economic Circle, the complementarity of Linyi's commercial logistics, Jining's cultural tourism and Zaozhuang's lithium battery industry has promoted the transformation of peripheral cities from "single adsorption" to "two-way interaction", forming a "Southern Shandong linkage axis" to fill the southern gap in Jinan and Qingdao radiation.

4. Conclusion

The county economy of Shandong Province has obvious agglomeration characteristics. Lights spread along the Jiaoji Railway, the Yellow River coast and the peninsula coastline to the junction of prefecture-level cities. For example, the light belts of Yantai and Weihai meet at Muping District, and the light and shadow of Zibo and Jinan merge at Zhoucun District. This indicates that resources are accelerating to flow to areas with higher efficiency, forming characteristic industrial clusters such as Jiaodong marine engineering equipment cluster, Zibo fluorosilicon new material belt and southern Shandong lithium battery industrial cluster. The county economic spatial pattern of Shandong Province presents the characteristics of "stable dominant direction, overall spatial expansion and local gravity center fine-tuning". The long-term dominant extension direction is northeast-southwest. With the enhancement of county economic radiation capacity, the overall economic space continues to expand. The economic gravity of each prefecture-level city in Shandong Province presents a spatiotemporal pattern of "dual-core dominance, sub-core circle linkage and peripheral catch-up". The radiation range of core cities such as Jinan and Qingdao continues to expand, sub-core cities form regional linkage circles, and peripheral prefecture-level cities show the late-developing characteristics of one-way adsorption. In the future, it is necessary to further strengthen the economic quality improvement of peripheral prefecture-level cities and the improvement of road networks in the region to promote the transformation from "one-way adsorption" to "two-way interaction".

Funding

Philosophy and Social Science Research Project of Universities in Shandong Province (Project No.: 2025ZSYB188)

Disclosure statement

The authors declare no conflict of interest.

References

[1] Wang J, Zhang W, Zhao R, et al., 2025, Measurement of High-Quality Economic Development Level and Regional Difference Analysis in Shandong Province. Shanghai Business, 2025(11): 127–129.

[2] Wang X, Huang L, 2018, Nighttime Light Data and Its Application in Economic Research. Economic Perspectives, 2018(10): 75–87.

[3] Ni J, Yang J, Xu D, et al., 2016, China's Economic Spatial Pattern Based on DMSP/OLS Nighttime Light Data. Journal of Central China Normal University (Natural Sciences), 50(6): 930–936.

[4] Xi C, 2011, Using Luminosity Data as a Proxy for Economic Statistics. Proceedings of the National Academy of Sciences of the United States of America, 108(21): 8589–8594.

[5] Vernon J, Adam S, 2012, Measuring Economic Growth from Outer Space. The American Economic Review, 102(2): 994–1028.

[6] Chen J, Zhuo L, Shi P, et al., 2003, Study on China's Urbanization Process Based on DMSP/OLS Data: Construction of Light Index Reflecting Regional Urbanization Level. Journal of Remote Sensing, 2003(3): 168–175+241.

[7] Wei K, Sun J, Zhang Z, et al., 2021, Spatial Simulation of GDP in Shanxi Province Based on NPP-VIIRS Nighttime Light Data. Journal of Zhejiang University (Science Edition), 48(6): 735–740+749.

[8] Wu W, 2021, Spatiotemporal Evolution Analysis of Unbalanced County Economic Development in the Yellow River Basin. Statistics & Decision, 37(21): 132–135.

[9] Guo H, Ma X, 2020, Evolution of Economic Spatial Pattern and Centrality Measurement in Huaihai Economic Zone Based on Nighttime Light Data. Geography and Geo-Information Science, 36(2): 34–40+125.

[10] Wang X, Wu D, Wang H, 2006, Quantitative Calculation of Economic Connections Between Cities. Urban Development Studies, 2006(3): 55–59.

[11] Niu Z, Yang X, Chen C, et al., 2024, Analysis of Urban Economic Development Characteristics in Chengdu-Chongqing Urban Agglomeration Combined with Nighttime Light Remote Sensing. Remote Sensing for Natural Resources, 36(4): 272–281.

[12] Zhang Z, Xue P, Huang Q, et al., 2025, Analysis on Development and Evolution Characteristics of Chengdu-Chongqing Twin-City Economic Circle Based on NPP/VIIRS Time-Series Remote Sensing Images. Bulletin of Surveying and Mapping, 2025(S2): 35–41.

[13] Hai Y, Chen H, Zhang H, et al., 2025, Spatiotemporal Pattern Evolution and Influencing Factors of County Economic Differences in Sichuan Province Based on Nighttime Light Data. Journal of Sichuan Normal University (Natural Sciences), 48(2): 231–241.

[14] Liu S, Xue L, 2021, Exploring Spatiotemporal Changes of Economic Development in Shaanxi Using Nighttime Light Data. Remote Sensing Information, 36(3): 113–121.

[15] Li D, Yu H, Li X, 2017, Analysis of Spatiotemporal Pattern of Urban Development in Countries Along the "Belt and

Road" Based on Nighttime Light Remote Sensing Images. Geomatics and Information Science of Wuhan University, 42(6): 711–720.

[16] Sun J, Luo B, 2016, Research on Economic Connections Between Beijing-Tianjin-Hebei Cities Based on Modified Gravity Model. Inquiry into Economic Issues, 2016(8):71–75.

[17] Research Group of Business Management Department of the People's Bank of China, Yang W, 2019, Measurement of Urban Economic Gravity in China's Three Major Urban Agglomerations and Its Enlightenment for Coordinated Development of Beijing-Tianjin-Hebei. Finance Forum, 24(4):71–80.