International Journal of Asian Social Science Research; Vol.3, No.1; 2026
E-ISSN: 3006-2179 P-ISSN：3006-754X
DOI: https://doi.org/10.70267/ijassr.260301.0112
Published by: Zeus Press

Spatial Responses to the Polarization: Trickle-Down Effect in Hunan Based on Remote Sensing

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Abstract

How regional spatial patterns adjust to the shifting balance between economic polarization and trickle-down effects remains insufficiently understood, especially in rapidly developing regions such as Hunan Province. A Regional Economic Score (RES) system is established using the entropy-weight method to depict long-term development trends, while the coefficient of variation and Theil index reveal a shift from polarization to convergence. A provincial core－periphery interaction model incorporating economic linkage strength further captures the radiation and spillover roles of the Chang-Zhu-Tan metropolitan area. Nighttime light-derived indicators, including centroid shifts and standard deviation ellipses, provide intuitive spatial evidence that complements statistical results and reflects general patterns of built-up area evolution. The analysis shows that Hunan’s development trajectory moved from a strong center-driven agglomeration toward a more multi-nodal, spillover-enhanced structure, with core cities exerting sustained positive influence on surrounding regions and stronger linkages reinforcing collaborative dynamics. Overall, the convergence of temporal, spatial, and economic evidence reveals clear surface manifestations of the polarization-trickle-down effect and offers empirical insights for provincial planning and coordinated regional development.

Keywords

remote sensing, urban built-up areas, polarization-trickling down effects, nighttime light data, Hunan province

1. Introduction

China’s rapid economic growth and urbanization have strengthened the agglomeration advantages of major cities while enabling outward diffusion through industrial relocation, transport connectivity, and population mobility, a process generally conceptualized as the polarization–trickle-down effect [1]. In spatial terms, this effect is reflected in the expansion and increasing development intensity of urban built-up areas [2].

Remote sensing imagery and night-time light data provide key tools for identifying built-up area structures and expansions, thereby revealing the spatial responses of economic processes. Scholars have systematically summarized methodologies for delineating built-up areas from remote sensing images [3]. Comparative evaluations have assessed the accuracy and applicability of night-time-light–based extraction methods [4]. Further studies have highlighted the need for differentiated threshold selection based on urban morphological types [5]. Recent analyses have investigated the spatial heterogeneity, driving forces, and urban–economic coupling in provincial and municipal built-up area expansions [6]. Other studies have revealed axial migration patterns and shifting spatial centers associated with city expansion [7]. National-scale assessments have demonstrated regional differences in expansion stages and efficiency [8]. Bibliometric analyses further show that night-time light remote sensing is increasingly integrated into urbanization and spatial-economic studies [9]. The theoretical foundation for polarization and diffusion dynamics is rooted in Hirschman's model of unbalanced growth [10]. Empirical studies using multi-source remote sensing have demonstrated strong correlations between built-up area expansion and economic growth in major cities [11]. Night-time-light–based analyses have revealed patterns of agglomeration and cooperative diffusion in metropolitan regions [12]. Studies of the Dongting Lake urban agglomeration have shown periodicity and enclave-like expansion patterns consistent with regional economic rhythms [13].

However, most existing work focuses on single cities or intra-urban-agglomeration dynamics, leaving provincial-scale economic–spatial interactions insufficiently explored. Taking Hunan Province as the study area, this research integrates multi-temporal remote sensing imagery, night-time light datasets, and socioeconomic statistics to achieve four aims: identifying the spatiotemporal manifestations of polarization–trickle-down effects; characterizing built-up area patterns and evolution across cities; summarizing center–periphery economic-spatial–spatial interaction modes; and proposing generalizable provincial-scale mechanisms to support coordinated regional development.

2. Study Area and Data Sources

2.1 Study Area

This study focuses on Hunan Province, located in central China along the middle reaches of the Yangtze River. The province is traversed by its largest river, the Xiangjiang, and spans from 108°47′ to 114°15′ east longitude and 24°38′ to 30°08′ north latitude, covering a total area of 211,800 square kilometers [14]. Hunan exhibits a pronounced "strong provincial capital" pattern in its economic development. In 2024, the gross domestic product of Changsha reached 1,526.878 billion yuan, accounting for over 28.68 percent of the provincial total and maintaining an absolute advantage within the province [15]. Other cities display varying degrees of dependence on and feedback from Changsha in terms of industrial transfer and factor mobility. Such marked regional disparities provide an ideal context for analyzing the relationship between urban built-up area patterns and the polarization–trickle-down effect.

2.2 Data Sources

The data used in this study include both remote sensing imagery and socio-economic statistics. Remote sensing data consist of Landsat 7 TM C2 L2 imagery and nighttime light data covering the period from 2000 to 2020. Landsat imagery was obtained from the Geospatial Data Cloud. Nighttime light data were sourced from the China Long-term Annual Artificial Nighttime Light Dataset (PANDA_CHINA) [16], and the years 2000, 2005, 2010, 2015, and 2020 were selected as sample years due to the availability of ground-validated observations. Socio-economic statistics for Hunan Province were primarily derived from the Hunan Statistical Yearbook and the China City Statistical Yearbook, with electronic versions accessed via the China Research Data Service Platform. The integration and standardization of these multi-source datasets form a comprehensive database for the empirical analysis conducted in this study.

3. Research Methods and Analytical Framework

This study aims to systematically measure the polarization–trickle-down effect in Hunan Province from two dimensions: overall development level and spatial pattern evolution. The technical framework is illustrated in Figure 1, while the theoretical underpinnings are summarized in Table 1.

Figure 1: Research framework(Picture credit: Original).

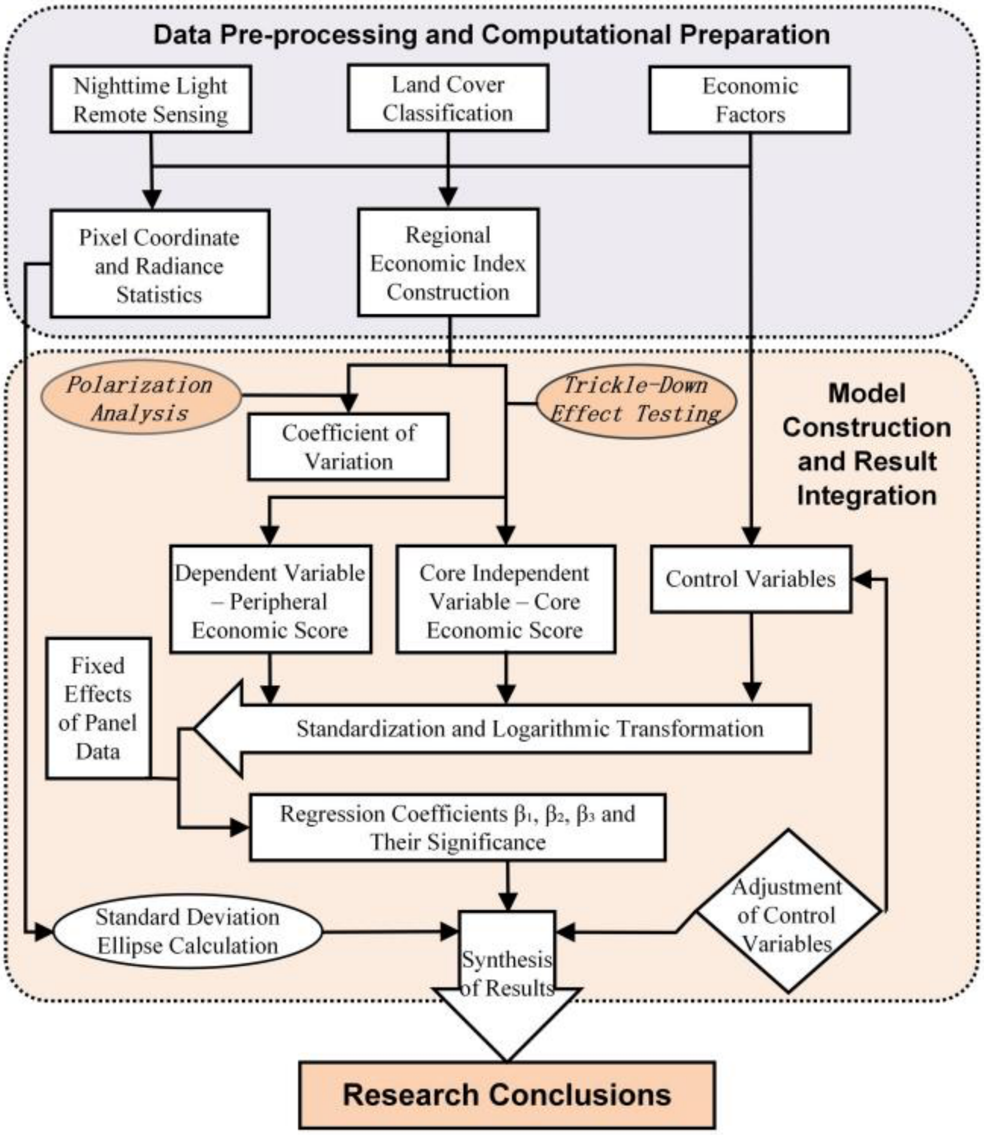


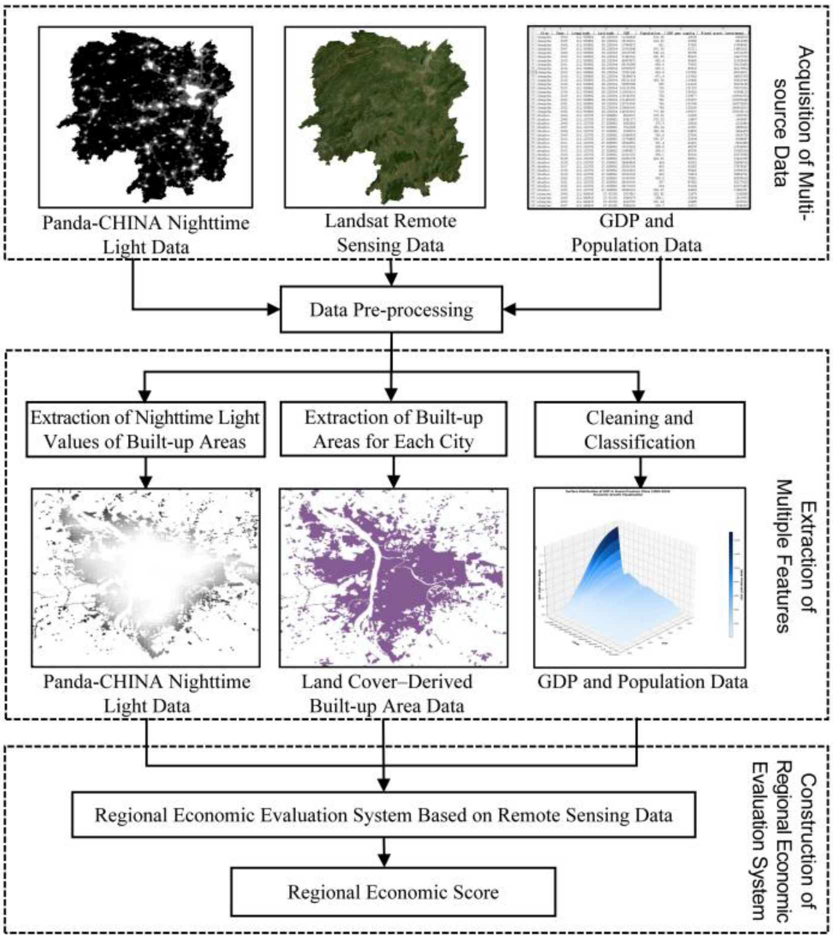
Table 1: Theoretical basis of the study.

Component / Step	**Corresponding Theory / Method**	**Source / Reference**
RES Multidimensional Indicator Weights	Entropy Weight Method	Indicator System in Table 2
Quantification of the Polarization–Trickle-Down Effect	Hirschman's Polarization–Trickle-Down Theory	Coefficient of Variation / Theil Index
Economic Linkage Intensity (Gravity Model)	Spatial Interaction Theory	Formula for Linkage_{i,t}
Centroid Migration and Standard Deviation Ellipse	Spatial Analysis in Economic Geography	Application of Nighttime Light Data
Trickle-Down Effect Pathway Testing	Interaction-Term Model Design	Fixed-Effects Panel Data

3.1 Quantitative Model of the Polarization–Trickle-Down Effect Based on Regional Economic Scores

To overcome the limitations of single indicators, this study first draws on the approach proposed by Liu Zhiyang and colleagues to construct a multidimensional Regional Economic Score (RES), which serves as the core measure of overall regional development [17]. The specific procedure is described as Figure 2.

Figure 2: Analytical workflow for the regional economic score(Picture credit: Original).



3.1.1 Construction of the Regional Economic Score System

Using the entropy weight method, the evaluation system is built from five dimensions—average nightlight intensity of built-up areas, built-up area size, per capita GDP, total nightlight intensity of built-up areas, and the built-up area expansion rate—as summarized in Table 2. The indicator data are derived from land use data interpreted from Landsat remote sensing imagery, including artificial surface areas, PANDA_CHINA nighttime light data for total light intensity, and statistical yearbooks for GDP and population. Using these indicators, regional economic scores $S_{i,t}$ are calculated for each city in Hunan Province for the years 2000, 2010, and 2020, where *i* represents the city and *t* represents the year.

Table 2: Indicator system for regional economic evaluation

Objective Level	Indicator	Weight
Regional Economic Score (RES)	Average nighttime light intensity of built-up areas	0.2730
	Built-up area	0.1240
	GDP per capita	0.2653
	Total nighttime light intensity of built-up areas	0.2639
	Built-up area expansion rate	0.0737

3.1.2 Measurement of Regional Disparities (Polarization Analysis)

To capture the evolution of regional economic differences, two indicators based on the regional economic scores are employed.

The coefficient of variation (CV_{Scoret}) is defined as：

$$CV_{Scoret} = \frac{\sigma_{S,t}}{\mu_{S,t}} \quad (1)$$

where $\sigma_{S,t}$ and $\mu_{S,t}$ are the standard deviation and mean of the regional economic scores of all cities in year *t*. An increase in this value indicates a widening of regional economic disparities, reflecting an intensified polarization effect.

The Theil index (T_{Scoret}) is defined as

$$T_{Scoret} = \sum_{i=1}^{N} \left(\frac{S_{i,t}}{S_t}\right) ln\left(\frac{S_{i,t}/S_t}{P_{i,t}/P_t}\right) \quad (2)$$

where S_t and P_t represent the total regional economic score and total population of all cities in year *t*. This index measures the inconsistency between economic distribution and population distribution, with higher values indicating greater imbalance.

3.1.3 Core–Periphery Interaction Model (Trickle-Down Effect Test)

A panel data fixed-effects model is constructed to examine whether the development of the core region, namely the Chang-Zhu-Tan urban agglomeration, produces a trickle-down effect on peripheral cities:

$$ln\left(S_{periphery,i,t}\right) = \beta_0 + \beta_1\, ln\left(S_{core,t}\right) + \beta_2 Linkage_{i,t} + \beta_3\left(Linkage_{i,t} \times ln\, S_{core,t}\right) + \gamma X_{i,t} + \alpha_i + \lambda_t + \epsilon_{i,t} \quad (3)$$

where $S_{periphery,i,t}$ denotes the regional economic score of peripheral city *i* in year *t*, and $S_{core,t}$ represents the regional economic score of the core cities in year *t*. A significantly positive β_1 indicates the presence of a trickle-down effect. $Linkage_{i,t}$ measures the economic connection strength between city *i* and the core, calculated using an improved gravity model:

$$Linkage_{i,t} = \frac{S_{core,t} \times S_{i,t}}{(Distance_{i,core})^2} \quad (4)$$

The interaction term $Linkage_{i,t} \times S_{core,t}$ is included to examine whether the trickle-down effect depends on the strength of economic connections. A significantly positive β_3 indicates that the trickle-down effect may be associated with the intensity of these economic links. $X_{i,t}$ is a set of control variables, including the logarithm of fixed asset investment and the logarithm of the number of university students.

3.2 Spatial Pattern Analysis Based on Nighttime Light Data

To provide spatial visualization evidence for the quantitative model, this study adopts the method of Samuha Danshanbai et al. (2024) using calibrated and integrated nighttime light data to analyze the spatial orientation, clustering, and pattern characteristics of economic development [18].

3.2.1 Economic Center of Gravity Migration

The economic center of gravity represents the spatial equilibrium point of regional economic development. Its coordinates (G_x,G_y) are calculated as

$$G_x = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}, G_y = \frac{\sum_{i=1}^{n} w_i y_i}{\sum_{i=1}^{n} w_i} \quad (5)$$

where w_i is the nightlight intensity of pixel *i* and (x_i,y_i) are its geographic coordinates. The trajectory of the center of gravity illustrates the spatial direction of economic expansion.

3.2.2 Standard Deviation Ellipse

A standard deviation ellipse is used to characterize the spatial distribution, orientation, and concentration of economic activity through its centroid, azimuth angle α, and semi-axes σ_x and σ_y.

$$tan\,\alpha = \frac{\left(\sum_{i=1}^{n} w_i^2 \bar{x}_i^2 - \sum_{i=1}^{n} w_i^2 \bar{y}_i^2\right)}{2\sum_{i=1}^{n} w_i^2 x_i^2 y_i^2} + \frac{\sqrt{\left(\sum_{i=1}^{n} w_i^2 \bar{x}_i^2 - \sum_{i=1}^{n} w_i^2 \bar{y}_i^2\right) + 4\sum_{i=1}^{n} w_i^2 x_i^2 y_i^2}}{2\sum_{i=1}^{n} w_i^2 x_i^2 y_i^2} \tag{6}$$

The formulas for calculating σ_x and σ_y are as follows:

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n}(w_i \bar{x}_i \cos\alpha - w_i \bar{x}_i \sin\alpha)^2}{\sum_{i=1}^{n} w_i^2}} \tag{7}$$

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^{n}(w_i \bar{x}_i \sin\alpha - w_i \bar{x}_i \cos\alpha)^2}{\sum_{i=1}^{n} w_i^2}} \tag{8}$$

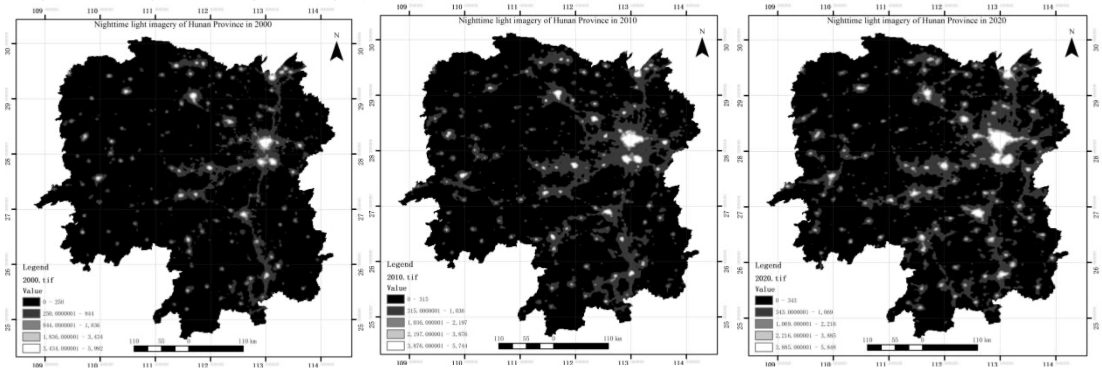
The tangent of the azimuth $\tan\alpha$ represents the deviation of pixel i's coordinates from the ellipse centroid. The values of σ_x and σ_y represent the lengths of the ellipse's semi-major and semi-minor axes, respectively. A decreasing ellipse area combined with an increasing flattening ratio indicates that the trend of economic development is becoming increasingly concentrated.

4. Data Analysis and Results

4.1 Construction of Regional Economic Scores

Based on the entropy weight method, a regional economic evaluation system was established for Hunan Province, quantifying economic development of each city through five indicators: average nighttime light intensity of built-up areas, built-up area size, per capita GDP, total nighttime light intensity, and built-up area expansion rate. Using the calculated weights, the regional economic scores (RES) for 13 cities and prefectures, excluding Xiangxi Autonomous Prefecture, in 2000, 2010, and 2020 were obtained. Overall, Hunan Province exhibits significant economic growth, with the Chang-Zhu-Tan urban agglomeration leading, while remote areas such as Zhangjiajie and Huaihua scored lower. Over time, most cities improved, reflecting overall provincial economic progress.

Figure 3: Nighttime light imagery of Hunan Province in 2000, 2010, and 2020(Picture credit: Original).



Nighttime light intensity serves as a key indicator of economic activity, closely related to population density, industrial activity, and urbanization. Figure 3 illustrates the spatial distribution of nighttime lights in 2000, 2010, and 2020. In 2000, lights were weak, concentrated in core cities such as Changsha, Zhuzhou, and Xiangtan, indicating limited economic activity. By 2010, light intensity had strengthened, core areas expanded, and surrounding cities such as Yueyang and Hengyang began showing prominent lights, reflecting accelerated industrialization and urbanization. In 2020, nighttime light coverage further expanded, forming contiguous high-intensity areas in the Chang-Zhu-Tan agglomeration, with scattered lights even in remote regions, indicating broader and deeper economic activity. These changes visually capture Hunan's economic expansion over two decades and the enhanced radiative influence of core areas. Nighttime lights not only reflect overall economic growth but also reveal spatial disparities in development.

Changes in land cover are closely linked to regional economic development. Built-up area expansion increased the corresponding indicator score and indirectly boosted per capita GDP through investment and employment. From 2000 to 2020, urbanization progressed rapidly but unevenly: the Chang-Zhu-Tan region experienced dense expansion, whereas Xiangxi's growth was limited by terrain. Land cover classification results validate the entropy weight system and highlight the role of land-use policies in regional economic coordination.

Figure 4: Changes in the regional economic scores of cities across three periods(Picture credit: Original).

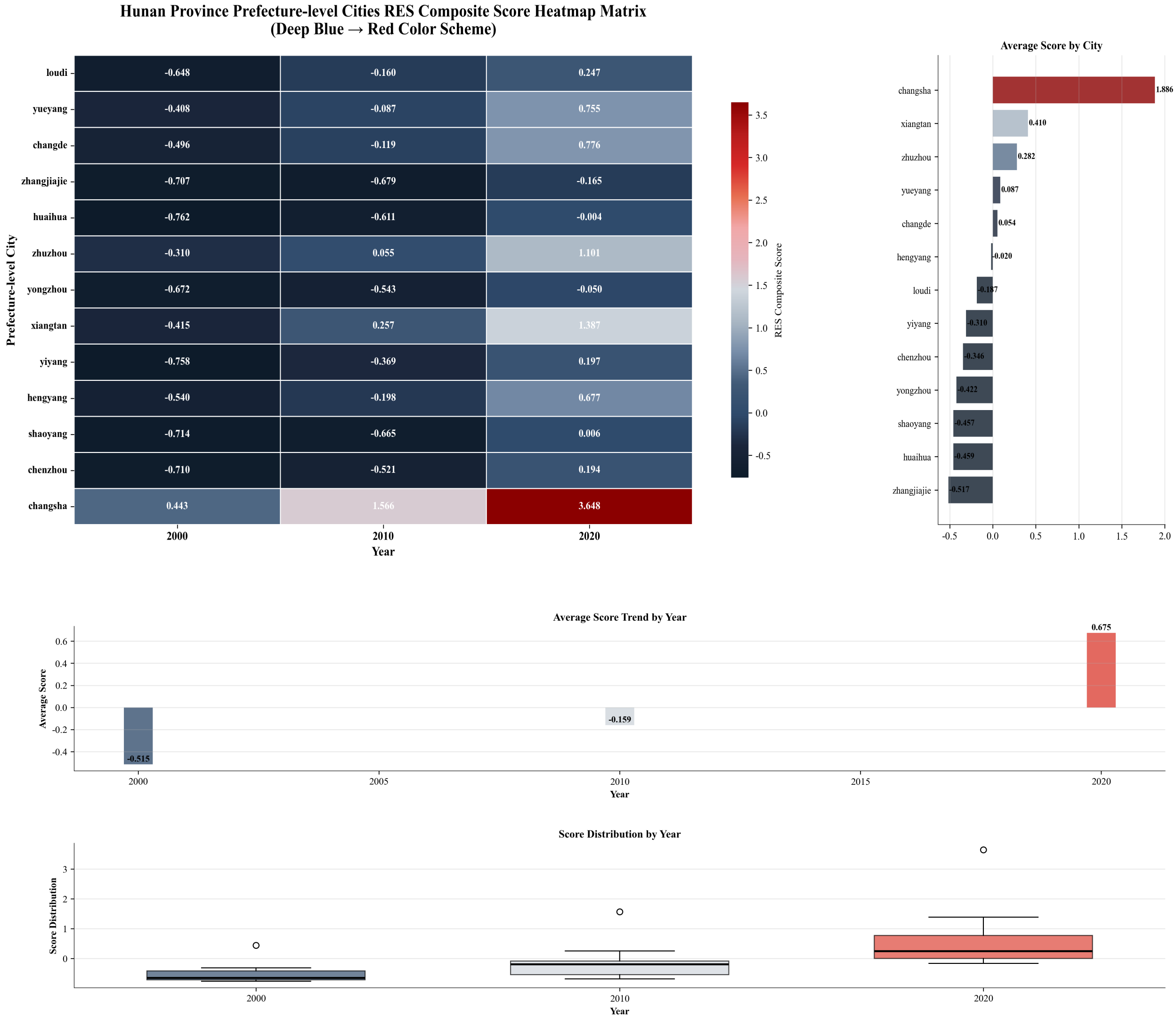


Figure 4 presents a heatmap of RES scores across 14 cities for 2000, 2010, and 2020. In 2000, most cities scored low, with only Changsha positive (0.443), indicating overall economic lag. By 2010, Changsha rose sharply to 1.566, Zhuzhou and Xiangtan became positive, while Xiangxi cities remained negative, reinforcing the core–periphery structure. In 2020, scores improved province-wide, with Changsha reaching 3.648 and notable growth in Yueyang, Changde, and Zhuzhou, while some remote areas approached zero, reflecting provincial development trends. Temporally, scores consistently improved, showing overall economic growth. Spatially, high-value areas remained concentrated in Chang-Zhu-Tan, while low-value zones were in Xiangxi and southern Hunan. This pattern aligns with the contributions of entropy-weighted indicators, demonstrating rapid growth and spatial restructuring; nighttime light, land cover, and RES scores mutually validate each other.

4.2 Polarization Evolution Revealed by Regional Economic Scores

Using the coefficient of variation (CV) and Theil index, Figure 5 and Figure 6 depict core–periphery disparities and changes across regions. Hunan's regional economic differences show clear dynamic evolution:

Figure 5: Measurement of core–periphery disparities(Picture credit: Original).

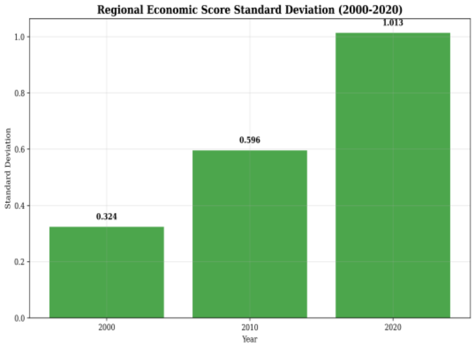
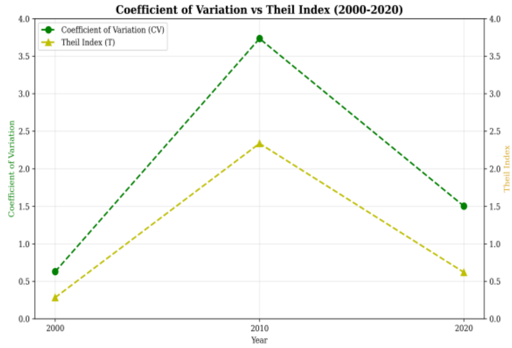


Figure 6: Coefficient of variation and Theil index(Picture credit: Original).



Stage 1: Dominance of Polarization (2000–2010)

Between 2000 and 2010, regional disparities expanded markedly. CV rose from 0.6288 to 3.7346, and the Theil index from 0.2836 to 2.3371, reflecting synchronized growth in relative differences and mismatched distributions. Production factors concentrated in the Chang-Zhu-Tan core, with Changsha, Zhuzhou, and Xiangtan forming pronounced growth poles due to policy and location advantages. Peripheral cities such as Xiangxi and Huaihua lagged, exacerbating absolute and structural imbalances. The standard deviation increased from 0.3239 to 0.5956, confirming rapid growth in absolute disparities. The dispersion of scores between core and periphery strengthened spatial differentiation, consistent with Hirschman's polarization theory, where early-stage resource concentration in core areas temporarily widens regional gaps.

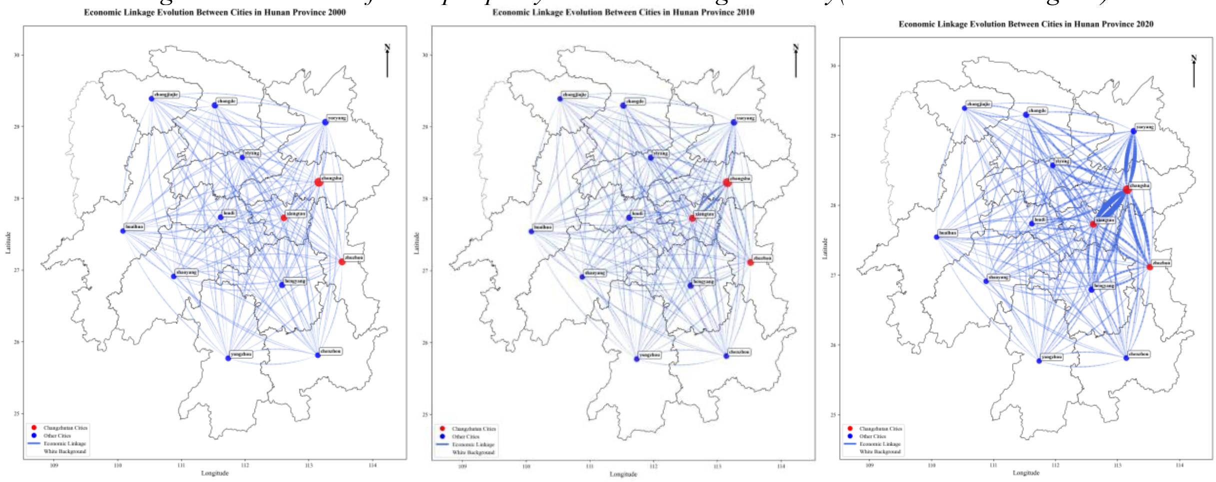
Stage 2: Emergence of Trickle-Down Effects (2010–2020)

After 2010, the trend of widening disparities began to structurally reverse. By 2020, the Theil index declined from 2.3371 to 0.6201, and CV adjusted to 1.5023, still above 2000 levels but significantly improved from 2010, indicating reduced mismatch between economic and population distribution. This reflects the initial emergence of trickle-down effects: as core cities grow, they stimulate peripheral development via industrial transfer and infrastructure connectivity. The trajectory of "initial expansion followed by contraction" aligns with polarization–trickle-down theory, where early growth poles aggregate resources, followed by outward spillover promoting peripheral growth.

4.3 Core–Periphery Interaction Model Testing

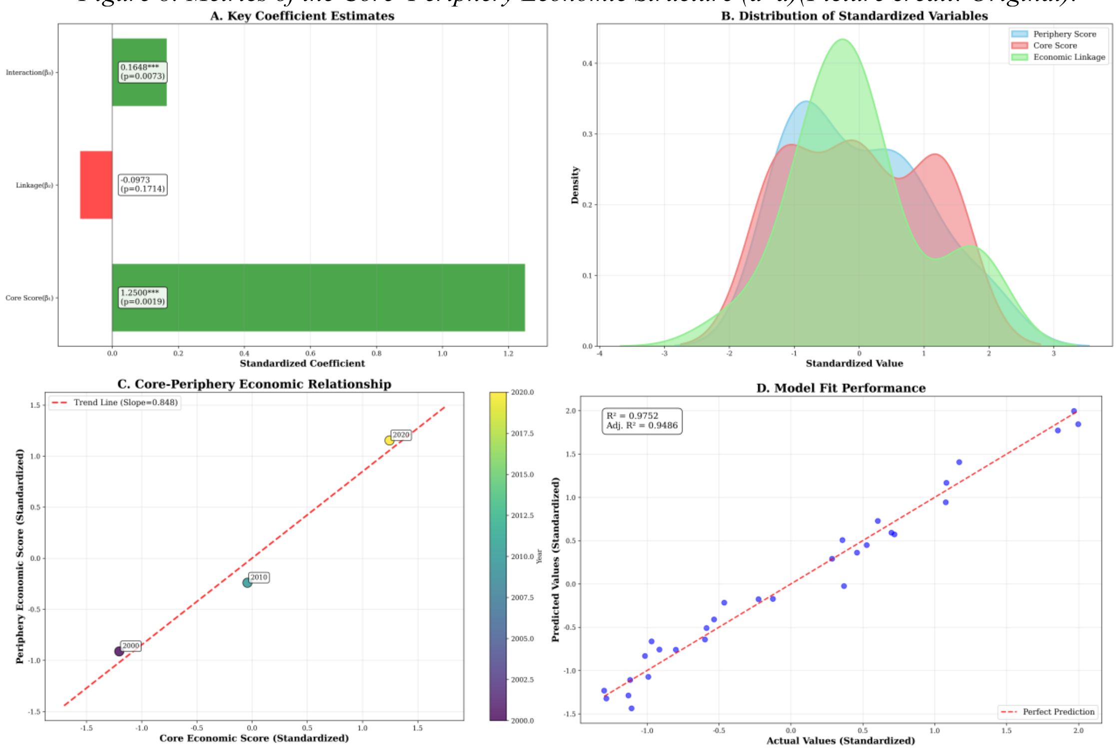
To analyze the interaction mechanism, an economic linkage index between cities was constructed based on a gravity model, and its spatial evolution is examined. Figure 7 shows link intensity by line thickness and color. From 2000 to 2020, Hunan's network evolved as follows: in 2000, weak links concentrated in Chang-Zhu-Tan formed a "star-shaped" structure with minimal peripheral connections. By 2010, internal links strengthened, secondary hubs appeared, and the economic reach extended along transport axes such as the Beijing–Guangzhou line. In 2020, the network became more complex and polycentric, with Chang-Zhu-Tan's influence reaching southern and western Hunan and lateral links among periphery cities, indicating deeper regional integration.

Figure 7: Evolution of core–periphery economic linkage intensity(Picture credit: Original).



A panel data fixed-effects model tested trickle-down effects, with regression results summarized in Table 3. Results show the core economic score coefficient β_1=1.249961 ($p < 0.01$), significantly positive at the 1% level, confirming that Chang-Zhu-Tan's growth positively drives peripheral cities. The interaction term coefficient β3 =0.164834 ($p = 0.007291$) is also significantly positive, indicating that stronger economic links enhance trickle-down effects by 0.164834 units. The model shows high goodness-of-fit ($R^2 = 0.9752$) and a significant F-statistic, demonstrating reliability. Figure 8 visualizes standardized key coefficients, providing empirical support for core–periphery interactions.

Figure 8: Metrics of the Core–Periphery Economic Structure (a–d)(Picture credit: Original).



Figures 8-C and 8-D further illustrate coordinated growth: core and periphery scores both rise from 2000 to 2020, aligning along a 0.848 slope trendline. Scores were low in 2000, improved in 2010, and peaked in 2020, confirming ongoing trickle-down effects. High R^2 and a tight fit between predicted and observed values verify the model's reliability and the collaborative growth mechanism. Hunan has thus formed a robust pattern of core-led, regionally coordinated development.

Table 3: Regression results of the core–periphery interaction model

Variable	Coefficient	p-value	Significance	Variable
$S_{core,t}(\beta_1)$	1.249961	0.001877	Significant	$S_{core,t}(\beta_1)$
$Linkage_{i,t}\times S_{core,t}(\beta_3)$	0.164834	p=0.007291	Significant	$Linkage_{i,t}\times S_{core,t}(\beta_3)$
$Linkage_{i,t}(\beta_2)$	-0.097334	p=0.171391	Not Significant	$Linkage_{i,t}(\beta_2)$

4.4 Spatial Pattern Evidence of Economic Development

Nighttime light-based spatial analysis provides intuitive evidence for the RES model by assessing economic center and directional characteristics. Figure 9 shows total light increasing continuously, reflecting overall expansion. The standard deviation ellipse's axes shortened and became more circular around 2010, marking a transition from initially concentrated to more balanced spatial growth, consistent with the shift from late-stage polarization to trickle-down effects.

Figure 9: Directional indicators and changes in total nighttime light(Picture credit: Original).

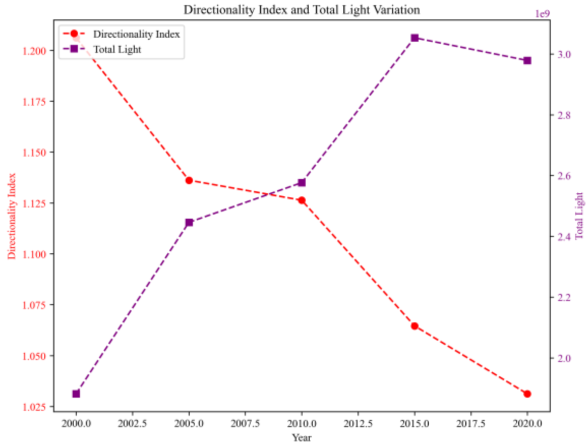
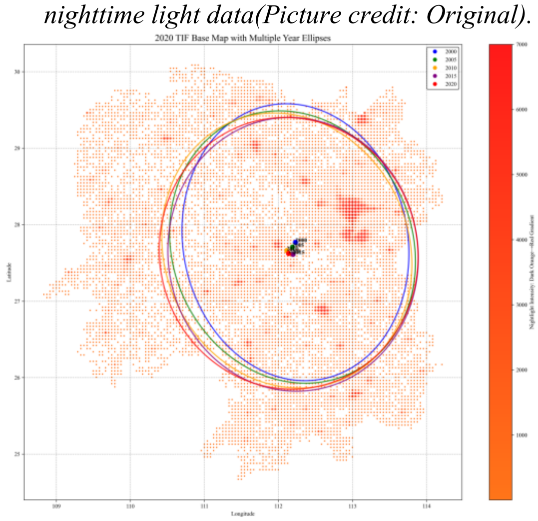


Figure 10 shows the ellipse's azimuth remained northwest–southeast, aligning with the Beijing–Guangzhou corridor, indicating long-term development along major transport axes. Economic center calculations reveal a consistent central-east location with a southwestward trajectory, confirming the growing influence of Chang-Zhu-Tan and faster development in peripheral areas absorbing core-region spillovers. Figure 10 also visualizes the center's migration and ellipse evolution over 2000–2020 [19].

Figure 10: Standard deviation ellipse of regional economic centroid migration in Hunan Province based on nighttime light data(Picture credit: Original).



5. Conclusions

The analysis of Hunan Province from 2000 to 2020 reveals a clear spatial evolution of economic polarization and the trickle-down effect, characterized by a transition from core concentration to coordinated diffusion. Strengthening the role of the Chang-Zhu-Tan urban agglomeration and enhancing its spillover efficiency is essential, as well as improving intercity connectivity and collaborative platforms to enable peripheral regions to absorb resources and benefits from core areas. During the study period, regional economic development displayed distinct phases: the 2000–2010 period was dominated by polarized expansion, whereas 2010–2020 saw relative convergence, with the Chang-Zhu-Tan growth pole initially widening regional disparities and later promoting more balanced development through spillover effects. The analysis of core–periphery interactions confirms the presence of significant trickle-down effects, where stronger economic ties correspond to greater peripheral gains, highlighting the importance of transportation and factor mobility. Spatial patterns derived from nighttime light data and standard deviation ellipses align closely with economic statistics, showing that urban expansion shifted from concentrated to dispersed, while the economic center of gravity moved southwest, emphasizing the increasing role of peripheral areas in sustaining provincial growth. The synchronous expansion of built-up areas and economic growth illustrates a shift from central agglomeration to multi-node linkages, confirming the surface-level spatial manifestation of polarization and trickle-down effects. Integrating remote sensing and nighttime light monitoring provides effective tools for tracking urban expansion, guiding land management, and informing regional planning decisions. Overall, Hunan's development reflects a coordinated spatial evolution where core and peripheral areas increasingly interact to support higher-quality, balanced regional growth.

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Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgment

This paper is an output of the science project.

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