

Measurement and Co-evolution Analysis of Economic Resilience and Ecological Efficiency in China's Provincial Regions: A Postprint

Authors: Zhou Xia

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Abstract

Coordinating the dynamic balance between economic resilience and ecological efficiency constitutes a critical approach for achieving regional sustainable development. This study examines 30 provinces in China, employing a combined weighting model and a global undesirable super-efficiency SBM model to measure economic resilience within the analytical framework of adaptive cycle theory and the Driver-Pressure-State-Response (DPSR) model, and ecological efficiency based on input-output theory, respectively. The co-evolutionary characteristics between economic resilience and ecological efficiency are depicted through an improved Haken model. The findings reveal: (1) Economic resilience capacity increased significantly during the sample observation period, with regional disparities expanding conspicuously, development imbalance between northern and southern regions, and a manifest “east-central-northeast-west” ladder effect. (2) The overall ecological efficiency level demonstrated a declining trend, with regional disparities undergoing “expansion-contraction-re-expansion” variations, significant ladder imbalance phenomena, and a spatial distribution decreasing from coastal to inland areas. (3) The co-evolution of economic resilience and ecological efficiency underwent three stages: stable, declining, and stable; ladder imbalance phenomena were essentially absent across regions; economic resilience, serving as the order parameter of co-evolution, dominates regional sustainable development.

Full Text

Measurement and Synergistic Evolution Analysis of Economic Resilience and Eco-efficiency at the Provincial Level in China

ZHOU Xia, WANG Jia

(School of Urban Economics and Management, Beijing University of Civil Engineering and Architecture, Beijing 100044, China)

Abstract: Integrating the dynamic balance between economic resilience and eco-efficiency represents a critical lever for achieving sustainable regional development. This study examines China's provincial-level regions, employing a combined weighting model and a global non-desired super-efficiency SBM model to measure economic resilience within the framework of adaptive cycle theory and the DPSR (Driving-Pressure-State-Response) model, and eco-efficiency within the input-output theory framework. An improved Haken model characterizes the synergistic evolution between economic resilience and eco-efficiency. The findings reveal: (1) Economic resilience capacity increased significantly during the observation period, with regional differences expanding markedly, unbalanced development between northern and southern regions, and a distinct "East-Central-Northeast-West" ladder effect. (2) Eco-efficiency levels exhibited an overall declining trend, with regional differences undergoing "expansion-contraction-re-expansion" changes, displaying significant stepwise imbalances and a spatial distribution decreasing from coastal to inland areas. (3) The synergistic evolution between economic resilience and eco-efficiency progressed through three stages: stability, decline, and stability. No significant stepwise imbalances existed between regions. Economic resilience, as the order parameter of synergistic evolution, dominates regional sustainable development.

Keywords: economic resilience; eco-efficiency; synergistic evolution; global non-desired super-efficiency SBM model; China

Economic resilience and eco-efficiency constitute key elements for sustainable socio-economic development. Currently, China's Lewis development model is losing momentum, the "three-phase superposition" effect continues to deepen, and external uncertainties are becoming more frequent, subjecting economic development to the triple pressures of "demand contraction, supply shocks, and weakened expectations." The conventional linear and static management frameworks can no longer address urban economic security issues, necessitating a resilience-oriented approach to guide stable urban economic system development. Simultaneously, cities face dilemmas among economic growth, resource constraints, and environmental protection. Balancing the relationships among environment, economy, and resources to coordinate the human-nature system represents an urgent requirement for high-quality urban development.

Economic resilience manifests as a city's capacity to resist and absorb risks promptly and effectively when facing acute shocks or chronic pressures, and to

achieve sustainable development through continuous structural adjustment via learning and adaptation. High-resilience economies can rapidly resist and recover from shocks to support eco-efficiency improvement, whereas low-resilience economies struggle to recover quickly, severely impacting eco-efficiency. Eco-efficiency emphasizes obtaining maximum desired output with minimal resource input and environmental damage, promoting technological progress, enhancing resource allocation efficiency and quality, and reducing resource-environment risks and ecological deficits, thereby improving economic resilience. The 20th Party Congress stressed adhering to economic security as the foundation, enhancing industrial chain and supply chain resilience and security levels, promoting green development, fostering harmonious coexistence between humans and nature, and implementing comprehensive conservation strategies to promote economical and intensive utilization of various resources. This highlights the critical practical issue of maintaining stable economic resilience growth while steadily improving eco-efficiency.

The resilience concept has evolved from engineering resilience to evolutionary resilience, achieving a transition from pursuing stable equilibrium to exploring adaptive development. Current research primarily measures economic resilience based on process and state. Process-based measurement often uses employment/unemployment data or GDP and other core variables to characterize the gap rate between actual and expected values during shock periods, requiring reference baseline states to identify external shocks. This approach focuses on resistance and recovery from short-term intense shocks but neglects the impact of “slow burn” on economic structure. Similar economic shocks may not occur simultaneously across regions, and regional economic stage divisions involve arbitrariness. Single-indicator resilience measurement exhibits specificity and heterogeneity, potentially causing biases. State-based measurement constructs comprehensive evaluation indicator systems from resource elements, resilience characteristics, and stages, enabling comprehensive representation of economic resilience dimensions, though specific measurement indicators vary.

Eco-efficiency, first proposed by Schaltegger and Sturm, has been applied to macro regional levels, meso industries, and micro enterprises and products. The academic community predominantly employs comprehensive indicator methods. Measurement methods are divided into parametric and non-parametric models based on whether the production function is known. Parametric models are represented by Stochastic Frontier Analysis (SFA), while non-parametric models are represented by Data Envelopment Analysis (DEA). Current research primarily treats economic resilience and eco-efficiency as independent objects, lacking exploration of their coordinated development relationship. This study integrates both as an interrelated system for empirical research on China’s provincial regions, constructing measurement systems for economic resilience and eco-efficiency based on adaptive cycle theory, the DPSR model, and input-output theory, while considering innovation quality, “dual carbon” constraints, and inflation factors. It further analyzes the synergistic relationship and evolutionary characteristics between economic resilience and eco-efficiency using

an improved Haken model, providing references for promoting high-quality economic development.

1.1 Economic Resilience Measurement

1.1.1 Indicator System Based on resilience genesis and the DPSR model, this study constructs an economic resilience evaluation framework integrated with adaptive cycle theory [Figure 1: see original paper]. Economic resilience represents a dynamic evolutionary process with adaptive cycles, where system components exhibit complex feedback and self-organizing interactions. The system dynamically changes when responding to endogenous and exogenous disturbances, establishing and enhancing adaptive learning capacity through structural and state adjustments. Each adaptive cycle comprises exploitation, conservation, release, and reorganization phases. To promote urban prosperity and achieve common prosperity, the economic system enters the rapid development exploitation phase, with gradually strengthening internal connections and capital accumulation, increasing industrial scale effects, and entering positive path dependence, thereby enhancing system resilience. In the conservation phase, resources continue accumulating while economic system potential reaches its peak, internal connections become overly dense, bearing numerous pressures, development gradually rigidifies, and path dependence shifts from positive to negative, decreasing resilience. The system suffers shocks, loses balance, and rapidly enters the release phase, experiencing structural decline, weak growth, and reduced internal connections. However, as old production modes and institutional forms break down, over-accumulated capital is released, making new resource utilization and economic transformation possible, with resilience gradually recovering. Resource release provides opportunities for experimentation and innovation in capital, structure, and organization within the system, entering the reorganization phase where new economic activities continuously emerge and disappear. Economic enterprises, structures, and organizations adapting to the new environment gradually shift to the exploitation phase, enhancing resilience. Based on this framework, this study evaluates China's provincial economic resilience across four dimensions: exploitation driving, conservation pressure, resistance-release, and recovery-reorganization.

Exploitation driving refers to the promotion of economic system development through population size, urbanization level, and consumption dimensions, representing the fundamental purpose of economic development to promote urban prosperity and meet people's aspirations for a better life. Conservation pressure refers to the vulnerability of economic systems when facing normalized risks from internal and external uncertainties, including foreign trade dependence, unemployment risk, and financial risk. Resistance-release refers to state changes in economic scale, industrial structure, asset investment, consumption retail, and social security when facing internal and external pressures. Recovery-reorganization refers to the recovery, innovation, and transformation capacity of economic systems after risks, reflecting self-learning adjustment, path renewal,

and economic transformation capabilities.

1.1.2 Combined Weighting Model The CRITIC model determines weights using indicator contrast intensity and conflict, effectively avoiding human interference in weight determination. However, it cannot measure data dispersion. The entropy method determines weights based on information entropy principles and variation coefficients, highlighting indicator dispersion. Therefore, constructing a combined weighting model integrating CRITIC and entropy methods can effectively compensate for respective limitations, with specific calculation formulas referenced in literature [27]. Since correlation coefficients may be negative in practice, absolute values are used.

1.2 Eco-efficiency Measurement

1.2.1 Eco-efficiency Indicator System Based on input-output theory, this study constructs an urban eco-efficiency measurement model through literature review. Eco-efficiency serves as a bridge connecting resources, economy, and environment, comprising actual resource input, economic benefits, and environmental losses. Following classical production function models and relevant research, this study selects labor, capital, energy, land, and water resources as input factors meeting basic urban production conditions. Economic benefits represent the value converted from products and services provided by urban production activities, typically reflected by GDP. Environmental impact represents undesired output, essentially the material difference between resource input and economic output, usually emitted in gas-liquid-solid forms. Existing research often uses “three wastes” emissions to measure undesired output. However, solid waste disposal systems are now well-developed—in 2020, general industrial solid waste dumping accounted for only 0.003% of generation, with minimal impact. To highlight low-carbon development as a key high-quality development component, this study comprehensively selects industrial wastewater, smoke dust, and CO₂ emissions to measure undesired output.

1.2.2 Global Non-desired Super-efficiency SBM Model The SBM model incorporates non-radial slack variables into the objective function, transcending radial and piecewise linear theory limitations. By considering undesired output, it effectively solves the “congestion” or “slack” issues in input-output elements that traditional radial and angle DEA models cause [20]. The super-efficiency SBM model combines super-efficiency and SBM advantages to distinguish efficient decision-making units [21]. To enable comparability of eco-efficiency values for the same decision unit across different years, a unique production frontier is constructed using all data, employing the global non-desired super-efficiency SBM model. Calculations are implemented in Matlab software, with specific formulas referenced in literature [22].

1.3 Improved Haken Model

The Haken model, proposed by Hermann Haken, analyzes complex system orderliness by eliminating fast variables to identify order parameters, studying evolution mechanisms and trends in self-organizing processes. In nonlinear dynamic system evolution, subsystems, parameters, or factors dominating overall system evolution are called slow variables—order parameters. Those enslaved by order parameters are called fast variables. The modeling steps are: (1) Propose assumptions and construct motion equations. Assuming q_1 as the order parameter and q_2 as the fast variable controlled by the order parameter, their synergistic development motion equations are:

$$\begin{cases} \dot{q}_1 = -\lambda_1 q_1 - a q_1 q_2 \\ \dot{q}_2 = -\lambda_2 q_2 + b q_1^2 \end{cases}$$

where λ_1 and λ_2 are damping coefficients for two subsystems; a and b are regression coefficients for relevant variables. (2) Solve parameters and test the “adiabatic approximation hypothesis” condition: $\lambda_2 > 0$. If satisfied, q_2 is the order parameter; otherwise, q_1 is the order parameter. (3) Solve system evolution equations. Instantly removing q_2 leaves q_1 insufficient time to change. Setting $\dot{q}_2 = 0$ yields $q_2 = \frac{b}{\lambda_2} q_1^2$. Substituting into the first equation gives the system evolution equation: $\dot{q}_1 = -\lambda_1 q_1 - \frac{ab}{\lambda_2} q_1^3$. (4) Solve potential functions. Integrating the negative of the evolution equation yields the potential function reflecting system state: $v = 0.5\lambda_1 q_1^2 + \frac{ab}{4\lambda_2} q_1^4$. (5) Solve system score values. Combining the evolution and potential equations and setting $\dot{q}_1 = 0$ yields the stable point $q_1^* = \sqrt{-\frac{\lambda_1 \lambda_2}{ab}}$. The distance between any system state parameter point and the stable point determines system state, with the system state evaluation function: $d = \sqrt{(q_1 - q_1^*)^2 + (q_2 - q_2^*)^2}$.

The original Haken model primarily served physics; applications in socioeconomic fields require improvements [24]: (1) Adjust motion equation forms. Since motion equations are designed for continuous random variables while socioeconomic variables often use discrete annual data, discretization is necessary. (2) Logarithmic processing. To avoid “spurious regression” from non-stationary time series in socioeconomic environments, variables require logarithmic transformation. (3) Add constant terms to motion equations. Systems experience random fluctuations, with macro observations fluctuating around mean values. Moreover, resilience and efficiency are inherent regional composite system attributes—even starting from zero, they can grow through innovation-driven and industrial adjustment measures, necessitating constant terms. After these adjustments, assuming economic resilience (JRR) as the order parameter, the synergistic evolution equations between economic resilience (JRR) and eco-efficiency (EGG) are:

$$\begin{cases} \ln JRR(t) = (1 - \lambda_1) \ln JRR(t-1) - a[\ln JRR(t-1)]^2 - b \ln JRR(t-1) \ln EGG(t-1) + c_1 \\ \ln EGG(t) = (1 - \lambda_2) \ln EGG(t-1) - c[\ln EGG(t-1)]^2 + d \ln JRR(t-1) \ln EGG(t-1) + c_2 \end{cases}$$

where c_1 and c_2 are equation constants; t is the time variable.

1.4 Kernel Density Estimation

Kernel density estimation, a non-parametric method using smooth curves to estimate random variable density functions, is commonly employed to characterize dynamic evolution features. Compared with parametric methods, it offers robustness, weak model dependence, and requires no prior data analysis knowledge. Specific calculation methods are referenced in literature [25].

1.5 Data Sources and Processing

Data primarily derive from the China Environmental Statistics Yearbook, China Energy Statistics Yearbook, China Urban Construction Statistics Yearbook, China Statistical Yearbook, National Science and Technology Expenditure Statistical Bulletin, EPS database, and provincial statistical yearbooks. Capital stock is calculated using the perpetual inventory method with 2000 as the base year and an economic depreciation rate of 9.6% [26]. CO₂ emissions data originate from the China Carbon Emission Accounts & Datasets, calculated using the 17-sector method [28]. Foreign trade dependence is measured by total import/export trade volume \times annual average exchange rate / GDP, with exchange rate data from the IMF International Financial Statistics. The financial institution loan-to-deposit ratio equals total loan balance / total deposit balance. Industrial structure diversification index is constructed based on the Herfindahl-Hirschman Index. Patent authorization quality uses the ratio of invention patent authorizations to total patent authorizations as a proxy. To eliminate inflation impacts on foreign trade dependence and related indicators, data are adjusted using the consumer price index with 2000 as the base period.

2 Spatiotemporal Differentiation Analysis

2.1 Provincial Economic Resilience Spatiotemporal Differentiation

Provincial economic resilience levels and kernel density estimates are shown in [Figure 2: see original paper]. Overall, national economic resilience remained relatively stable initially, then steadily increased after 2012, with the overall mean rising from 0.187 in 2001 to 0.494 in 2020, representing an average annual growth rate of approximately 5.18%. Regional differences expanded, with the coefficient of variation increasing from 0.324 to 0.498. Regionally, the eight comprehensive economic zones exhibited certain stepwise imbalances, with mean rankings: Northwest (0.235) < Northeast (0.306) < Southwest (0.363) < Central Yellow River (0.394) < Central Yangtze River (0.435) < North Coast (0.493) < South Coast (0.554) < East Coast (0.687). The Northwest region's value was 0.48 times the national mean, while the East Coast reached 1.39 times.

In dynamic evolution, national economic resilience showed a trend of agglomeration from low to high value areas and transition from bimodal to unimodal

distribution. Distribution location shows the kernel density curve continuously shifting rightward, with peak areas concentrated between 0.1-0.3, indicating generally low but continuously strengthening provincial resilience levels. Distribution morphology shows the curve evolving from “inverted U-shaped” to “inverted V-shaped,” with main peak values significantly declining and curve bandwidth gradually increasing, indicating dispersed regional economic resilience levels. In terms of extensibility, the right-side tail feature gradually becomes apparent and elongates, meaning the gap between high-resilience provinces and the overall average gradually widens, with absolute differences expanding. Polarization trends show side peaks gradually evolving into inconspicuous bulges, with bipolar tendencies disappearing and unipolar characteristics becoming increasingly prominent.

To further explore spatial non-equilibrium characteristics, natural breakpoint classification divides regions into five categories, with four time points selected for visualization [Figure 3: see original paper]. High-resilience regions gradually extended from the north coast to the east and south coasts, then fluctuated toward the middle Yellow River, middle Yangtze River, and southwest regions, showing obvious spatial differentiation and an “East-Central-Northeast-West” ladder distribution. Specifically, the eastern region, as a forerunner in economic development with solid industrial foundations, leading economic scale, and obvious innovation agglomeration effects, has gradually become a resilience leader. The central region’s rise strategy has achieved remarkable results, with overall upward trends in economic resilience development, surpassing the northeast region in 2015 and ranking second only to the eastern region, though slightly declining in 2020 due to pandemic impacts. The northeast region has good industrial foundations but imbalanced industrial structures, often at the front end of industrial chains, with slow private economic development, causing its economic resilience to remain stable and slightly decline after peaking in 2013. The western region has weak industrial development, with resilience values consistently at the national minimum.

North-south regional development is unbalanced, gradually transforming from “north strong, south weak” to “south strong, north weak.” The proportion of southern provinces exceeding the national average increased from 33.3% in 2001 to 61.5% in 2020. The south’s earlier reform and opening-up stimulated rapid economic vitality growth, weakening the north’s innate advantages from national strategies, international situations, and resource conditions. Since entering the new normal, the north’s high dependence on heavy chemical industries and lagging industrial upgrading, contrasted with the south’s faster marketization, higher openness, better business environment, and faster institutional reform, has led to gradually expanding north-south resilience gaps. Urban agglomeration advantages are prominent, with high-resilience regions located in core provinces of mature urban agglomerations like the Yangtze River Delta, Beijing-Tianjin-Hebei, and Pearl River Delta.

2.2 Provincial Eco-efficiency Spatiotemporal Differentiation

Provincial eco-efficiency levels and kernel density estimates are shown in [Figure 4: see original paper]. Overall, national eco-efficiency showed a declining trend, with the overall mean decreasing from 0.550 in 2001 to 0.302 in 2020, a drop of 54.95%. Regionally, China's eight comprehensive economic zones exhibited significant stepwise imbalances, with mean rankings: Northwest (0.210) < Northeast (0.233) < Southwest (0.254) < Central Yellow River (0.264) < Central Yangtze River (0.285) < North Coast (0.354) < East Coast (0.387) < South Coast (0.442). The South Coast reached 1.46 times the national mean, while the Northwest was only 0.69 times. The coefficient of variation curve showed a “N” shape, indicating regional differences expanded, contracted, then expanded again.

In dynamic evolution, eco-efficiency agglomerated from high to low value areas. Distribution location shows the kernel density curve first shifted left then slightly rightward, with peaks concentrated between 0.1-0.3, indicating generally low national eco-efficiency levels. Distribution morphology shows the curve's kurtosis transitioning from “evenly matched” to “one strong, many weak” in the first 10 years, with peaks continuously increasing and bandwidth gradually narrowing, indicating dynamic convergence. Subsequently, the curve showed expansion trends. In extensibility, the right-side tail feature gradually appeared, then weakened before strengthening again, indicating absolute differences first narrowed then increased.

To further explore spatial non-equilibrium characteristics, natural breakpoint classification divides eco-efficiency into five categories, with four time points visualized [Figure 5: see original paper]. Analysis reveals: (1) National eco-efficiency levels largely collapsed. Compared with 2001, low-efficiency areas emerged extensively in central and western regions by 2020. National eco-efficiency can be divided into two stages at 2011: the first stage saw continuous decline due to rapid foreign trade expansion causing resource-environment pressure; the second stage saw slowing decline and stabilization, reaching the lowest value in 2017 then slightly rising, as the extensive growth model became unsustainable and the economy transitioned to the “new normal.” (2) East-west gaps persist, with the east leading. The eastern region's eco-efficiency showed a clear declining trend, indicating it has not fully escaped extensive growth. Influenced by economic restructuring, ecological civilization strategy, and innovation promotion, eastern eco-efficiency began rising after bottoming out in 2017. The northeast's single industrial structure, extensive development mode, and “coal city clusters” phenomenon neglected economic quality and environmental benefits. Post-financial crisis, delayed SOE reform, poor business environment, and population outflow constrained industrial transformation, causing northeast eco-efficiency to fall from second to lowest nationally. Central provinces like Shanxi, Anhui, and Hubei, dominated by resource-based industries with high resource consumption but insufficient development, exhibited low eco-efficiency. The western region, despite GDP growth from the Western Development Strategy, showed promi-

ment “east decrease, west increase” in high-energy industries, remaining in early industrialization stages with weak innovation, low-level industrial structure, and insufficient green technology, resulting in the lowest eco-efficiency levels.

North-south balanced development slightly weakened. Southern eco-efficiency was slightly higher than the north, but the gap expanded after 2011. In 2020, the absolute difference in north-south eco-efficiency means first exceeded 0.05, with 61.5% of provinces exceeding the national average located in the south.

3 Synergistic Evolution Analysis

3.1 Order Parameter Identification

To exclude collinearity interference, linear regression collinearity diagnosis was performed on economic resilience and eco-efficiency. Variance Inflation Factor (VIF) values were 1.32 and 1.28, respectively, indicating no collinearity. Following Haken model principles, assumptions were proposed, evolution equations constructed, and parameters solved. Results show economic resilience (JRR) is the order parameter, with parameters: $\lambda_1 = 0.004772 > 0$, $\lambda_2 = 0.074923 > 0$, $a = -0.05628 < 0$, $b = 0.005961 > 0$. The system evolution equation is: $\dot{q}_1 = -0.00477q_1 + 0.004478q_1^3$. The potential function is: $v = 0.002386q_1^2 - 0.001271q_1^4$. Setting $\dot{q}_1 = 0$ yields potential function solutions: $q_1^* = 0$ and $q_1^* = 1.032336$. Since $q_1^* = 0$ is an unstable solution and both economic resilience and eco-efficiency values exceed 0, only the $q_1^* > 0$ portion is considered. Thus, the system stable point is (1.032336, 0.001271). The system state evaluation function is: $d = \sqrt{(q_1 - 1.032336)^2 + (q_2 - 0.001271)^2}$.

3.2 Spatiotemporal Characteristics of Synergistic Evolution

Provincial economic resilience and eco-efficiency synergy levels and kernel density curves calculated via the improved Haken model are shown in [Figure 6: see original paper]. Overall national changes can be divided into three stages using 2011 as a watershed: early stability (2001-2011) with synergy means stable around 0.893; middle decline (2011-2017) with synergy means slowly declining from 0.893 to 0.742, a 16.91% drop; and later stability (2017-2020) with synergy means stable around 0.742. Regional differences expanded at an “N-shaped” rate, with the coefficient of variation fluctuating from 5.42% to 13.71% to 14.51%, though no stepwise imbalances existed. Except for the East Coast (1.13 times national mean), other regional synergy means fluctuated within $\pm 10\%$ of the national average.

Dynamic evolution shows the national economic resilience synergy kernel density curve overall shifted leftward, with uneven shifting magnitude—small to large to small. Peak height declined, shape transitioned from “sharp-narrow” to “platform,” width increased, and bimodal shifted to unimodal, with obvious left-tail features and weakening side peaks, indicating synergy values became more dispersed with increasing absolute differences. Low-value provincial proportions

increased, with spatial gaps expanding annually. Polarization trends show side peaks gradually becoming inconspicuous bulges on the left tail, with bipolar tendencies disappearing and unipolar characteristics becoming prominent.

To further explore spatial evolution characteristics, natural breakpoint classification divides synergy into five stages: high-level synergy [0.893, 1], relatively high-level synergy [0.807, 0.893), medium-level synergy [0.742, 0.807), relatively low-level synergy [0.660, 0.742), and low-level synergy [0.528, 0.660). Four time points are visualized [Figure 7: see original paper]. Overall, low synergy areas spread from points to surfaces, east to central-west, and coastal to inland. In 2001, only Beijing was at medium-level synergy, with Hebei, Jiangsu, and Guangzhou at relatively high-level synergy, all located in north, east, and south coastal areas. By 2011, medium and relatively low-level synergy provinces spread to the middle Yellow River and middle Yangtze River regions. By 2020, relatively high-level synergy areas spread nationwide, though high-level synergy areas remained. In 2020, Qinghai, Ningxia, and Guizhou shifted from high-level to relatively high-level synergy, with all regions at relatively high-level synergy or below.

North-south regional synergy gaps are small. Using 2011 as a watershed, the south exceeded the north in the early stage, while the north exceeded the south in the later stage. The gap can be divided into two phases: 2001-2011 stable stage with fluctuations around 0.01, and 2011-2020 rapid decline stage with faster decreasing north-south differences. Low synergy areas are common in coastal and river provinces—75% of primary synergy provinces in 2001 were in north, east, and south coastal areas, while 62.5% of relatively low-level synergy provinces were in middle Yangtze River and middle Yellow River regions. Northwest China shows the most stable synergy, with Ningxia, Xinjiang, Gansu, and Qinghai experiencing the nation's lowest synergy declines (all <10%) from 2001-2020, maintaining relatively high-level synergy or above.

4 Discussion

This study's economic resilience conclusions align with Xie Huiqiang et al. [7] and Gao Lintong et al. [8], while eco-efficiency conclusions share overall trends with Zheng Defeng et al. [13] and Shen Weiteng et al. [14], though differences exist due to research perspectives, evaluation indicators, and measurement standards. The main contribution lies in placing economic resilience and eco-efficiency within a unified analytical framework to explore their spatiotemporal characteristics and synergistic evolution trends, expanding current economic resilience research perspectives and case applications. Results indicate a competitive-cooperative relationship between economic resilience and eco-efficiency. Future research should seize the opportunity to build a new development pattern with “dual circulation,” strengthening overall planning and strategic layout. With supply-side reform, industrial structure optimization, and scientific-technological innovation as leverage points, urban economic elements should be organically integrated to establish a market-oriented resource

allocation system balancing efficiency and resilience, promoting positive interactions between economic resilience and eco-efficiency to achieve sustainable and high-quality development of complex economic systems. However, this study only discusses levels and synergistic development states, with insufficient exploration of spatial difference driving mechanisms and optimization paths, requiring future investigation. Additionally, the research object is provincial-level regions, leaving county-level scales for future study.

5 Conclusions

- 1) **Economic Resilience:** Overall, economic resilience increased significantly during the observation period. Regionally, differences expanded. Dynamic evolution shows domestic economic resilience levels became more dispersed, absolute differences increased, and unipolar characteristics became prominent. Spatially, north-south development is unbalanced, transforming from “north strong, south weak” to “south strong, north weak,” showing an “East-Central-Northeast-West” ladder effect. Urban agglomeration advantages are prominent, with high-resilience regions concentrated in core provinces of mature urban agglomerations.
- 2) **Eco-efficiency:** Overall, national and regional eco-efficiency declined, with some provinces showing initial decline then rise. Regionally, the national coefficient of variation curve shows an “N” shape, with significant stepwise imbalances and “expansion-contraction-re-expansion” differences. Dynamic evolution shows kernel density curves first shifting left then slightly right, with kurtosis transitioning from “evenly matched” to “one strong, many weak,” peaks first increasing then decreasing, indicating low overall national levels, initial dynamic convergence then expanded concentration, and absolute differences first shrinking then expanding. Spatially, national eco-efficiency values largely collapsed, showing a “coastal-inland” decreasing distribution, with north-south balanced development slightly weakening.
- 3) **Synergistic Evolution:** The order parameter analysis shows economic resilience serves as the order parameter for China’s economic resilience-eco-efficiency synergistic evolution, enslaving eco-efficiency and dominating the path and direction. Overall changes divide into three stages at the 2011 node: stability, decline, and stability. Regionally, the national coefficient of variation rises at an “N-shaped” rate, with regional differences slightly expanding but small north-south gaps and basically no stepwise imbalances. Dynamic evolution shows kernel density curves shifting left, peak height declining, shape transitioning from “sharp-narrow” to “platform,” width increasing, bimodal to unimodal, with obvious left-tail features and weakening side peaks, indicating synergy values becoming more dispersed with increasing absolute differences. Spatially, low synergy areas spread from points to surfaces, east to central-west, coastal to inland, with northwest regions showing the most stable synergy.

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