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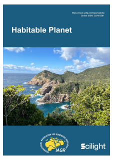

Article

Toward a Sustainable Future through Green Transformation: A Spatiotemporal Perspective on the Evolution of China's Ecological Efficiency

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ABSTRACT

Under the guidance of the "dual carbon" strategy and the Sustainable Development Goals, improving ecological efficiency has become a key pathway for promoting China's green transformation and high-quality development. This study aims to evaluate the spatiotemporal evolution of ecological efficiency and regional disparities across China. Using panel data from 30 provincial-level regions from 2012 to 2021, we construct an evaluation framework covering five dimensions: resource utilization, growth quality, green infrastructure, environmental governance, and ecological conservation. A unified assessment model is employed to measure provincial ecological efficiency, while Theil index decomposition and spatial autocorrelation analysis are used to examine temporal trends and spatial patterns. The results show that ecological efficiency in China has significantly improved over time, with regional gaps gradually narrowing. However, a persistent spatial pattern remains, characterized by high efficiency in the east, low efficiency in the west, rising levels in the central region, and fluctuations in the northeast. Intra-regional disparities are the main contributors to total variation, with greater heterogeneity in the eastern and western regions. Significant positive spatial clustering is observed in most years, with high–high clusters concentrated in central and eastern regions and low–low clusters prevailing in the west. These findings provide empirical support for regionally differentiated ecological governance and offer policy implications for advancing China's green transition.

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Research Highlights

- Evaluation of spatiotemporal evolution of ecological efficiency and regional disparities across China.
- High efficiency in the east, low efficiency in the west, rising levels in the central region, and fluctuations in the northeast.
- Empirical support for regionally differentiated ecological governance and offer policy implications for advancing China's green transition.

1. Introduction

In the context of the increasingly prominent challenges posed by global climate change and ecological degradation, ecological efficiency has emerged as a crucial pathway for countries striving to achieve a harmonious progression of both economic and environmental goals. Ecological efficiency not only aids in mitigating the ecological risks associated with climate change, but it also facilitates the optimization of energy structures and enhances resource utilization, thereby promoting sustainable economic growth [1]. In recent years, the international community has broadly recognized the green, low-carbon transition as a core strategy for achieving high-quality development, striving to balance economic prosperity with environmental conservation through enhanced energy efficiency and ecological performance.

Against this global backdrop, China, as the world's largest developing country, finds itself at a pivotal juncture in transitioning from high-speed growth to high-quality development. According to data released by the International Energy Agency (IEA), China's CO_2 emissions exceeded 11.9 billion tons in 2021, accounting for roughly one-third of global emissions, underscoring both the magnitude of its resource and environmental pressures and the urgency of accelerating a green and low-carbon transition. Meanwhile, according to data released by the National Energy Administration (NEA), the share of renewable energy in China's total installed power generation capacity exceeded 56% by the end of 2024, marking a historic high and reflecting the country's rapid progress in clean energy development. Over the coming decades, an ecological efficiency model driven by clean energy and green technological innovation is anticipated to be a key direction for China's ongoing economic and social advancement [2]. Promoting a societal green transition will not only alleviate pressing issues such as resource constraints and environmental pollution, but it will also optimize industrial structures, foster sustainable economic growth, improve the quality of life for residents, and contribute to broader societal equity and intergenerational sustainability. As a critical metric for evaluating the coordination between economic development and ecological integrity, ecological efficiency plays a central role in this process [3]. It reflects the capacity to maximize economic output under the constraints of resource inputs and environmental pressures, providing a robust indicator of regional ecological performance. Consequently, analyzing China's green transition through the lens of ecological efficiency is of profound theoretical and practical significance for assessing regional development performance, identifying disparities, and advancing the construction of an ecological civilization.

As a crucial indicator that balances economic development with ecological conservation, its core concept is to achieve maximum economic and social benefits with minimal resource. This concept extends traditional measures of production efficiency to encompass environmental dimensions, positioning itself as a pivotal tool for assessing the sustainability of economic activities. With the increasing global emphasis on green growth and low-carbon transitions, ecological efficiency has found widespread application in evaluating sustainable development at the national, regional, and industry levels [4]. It not only reflects the degree of alignment between resource inputs and pollution emissions, but also uncovers the pressures and constraints that economic growth imposes on the ecological environment, making it an essential benchmark for achieving a green economy and high-quality development.

For China, enhancing regional ecological efficiency holds significant strategic importance. On one hand, the deepening of economic restructuring and energy transformation has led to notable regional disparities in resource endowments, industrial structures, and the enforcement of environmental policies, resulting in clear spatial imbalances in ecological efficiency [5]. On the other hand, improving provincial ecological efficiency is a critical pathway for realizing the dual goals of the "dual carbon" targets and promoting regional coordination and green transformation. It plays an instrumental role in achieving both economic growth and environmental improvement.

Existing research on ecological efficiency primarily focuses on two areas. From the perspective of research themes, the existing literature can broadly be divided into studies on how to measure ecological efficiency and studies on what drives its variation across regions. The first is the measurement of ecological efficiency. A significant body of literature has conducted quantitative assessments of ecological efficiency across different regions, industries, and time periods, utilizing complex indicator systems and methodological advancements [6]. Commonly employed methods include Data Envelopment Analysis (DEA) and its extended forms, such as the SBM-DEA model, super-efficiency DEA model, and the Malmquist index model [7, 8]. These methods enable a comprehensive consideration of the relationships between economic output, resource consumption, and environmental pollution, thereby providing an objective reflection of the dynamic changes in ecological efficiency [9]. Additionally, some studies have incorporated methods such as Stochastic Frontier Analysis (SFA), the entropy method, and multi-criteria decision analysis, offering diverse analytical tools for evaluating ecological performance from various perspectives [10–12]. Overall, this strand of research has laid a solid methodological foundation for the quantitative evaluation of ecological efficiency.

Building on these measurement-oriented studies, a second major strand of the literature focuses on the driving forces behind ecological efficiency. The second area of focus is the analysis of factors influencing ecological efficiency. Existing studies generally agree that factors such as economic development level, industrial structure, energy efficiency, technological innovation capacity, environmental governance intensity, and policy and institutional frameworks all significantly impact regional ecological efficiency [13, 14]. Among these, economic structural upgrading and technological advancement are widely regarded as key drivers of ecological efficiency, while high energy dependency and disparities in environmental regulation are likely to exacerbate regional differences in ecological efficiency [15–17]. These findings indicate that ecological efficiency is not only a function of resource and environmental conditions, but is also deeply embedded in broader economic, technological, and institutional contexts, which provides an important basis for the design of differentiated regional policies.

In general, although significant progress has been made in both the measurement methods and the analysis of the factors influencing ecological efficiency, there remain several limitations. First, most studies focus on static measurements or comparisons across single time points, lacking a systematic exploration of the spatiotemporal dynamics and evolutionary characteristics of ecological efficiency. Second, there is insufficient analysis of the sources of regional disparities and spatial interdependence, with limited insight into the spatial clustering and differentiation patterns of ecological efficiency. Third, in constructing indicator systems, many studies tend to focus on either economic or environmental aspects, neglecting a comprehensive consideration of ecological, social, and resource dimensions. Overall, relatively few studies have simultaneously integrated a multidimensional evaluation framework with explicit decomposition of regional disparities and spatial correlation effects at the national scale, resulting in an incomplete understanding of the mechanisms shaping regional ecological efficiency.

In light of these gaps, this paper takes China's provincial administrative units as the research subjects, constructing an ecological efficiency evaluation system that covers five dimensions: resource utilization, growth quality, green development, environmental governance, and ecological protection. The paper employs a comprehensive evaluation model to measure the ecological efficiency of each province and integrates the Theil index and spatial autocorrelation analysis methods to systematically investigate the spatiotemporal evolution and regional disparities in ecological efficiency across Chinese provinces.

The potential contributions of this study are primarily reflected in two aspects. First, from a research perspective, this study adopts provincial units as the focus of analysis, constructing a comprehensive indicator system that encompasses multiple dimensions, including economic, social, resource, and environmental factors. By integrating an analysis of temporal evolution and spatial clustering characteristics, this study provides a more comprehensive understanding of the dynamic patterns of regional ecological efficiency in China compared to previous research. Second, in terms of both research content and practical significance, this study offers targeted policy recommendations, providing new empirical evidence for further exploration of the spatiotemporal characteristics of ecological efficiency. By linking fine-grained provincial measurements with a systematic examination of regional inequality and spatial agglomeration, this paper fills an potential gap in the literature on China's ecological efficiency and offers a more holistic analytical perspective for subsequent studies. Additionally, it makes a valuable contribution to the academic literature in relevant fields.

The remainder of this paper is structured as follows. Section 2 presents the research design, including the evaluation framework, methodological approach, and data sources. Section 3 reports the empirical results and analysis, focusing on the temporal evolution, regional disparities, and spatial patterns of ecological efficiency. Section 4 provides the conclusions and policy recommendations, and discusses the study's limitations and future research directions.

2. Research Design

2.1. Indicator System and Data Sources

This study identifies key indicators related to the development of ecological efficiency. Given considerations such as data availability, the study makes certain adjustments to commonly used ecological efficiency indicator systems, establishing a comprehensive evaluation framework for ecological efficiency in this research. In adjusting the indicator system, the study first ensures the scientific rigor of the selected indicators. This is achieved by grounding the indicators in reliable theoretical and empirical research, applying rigorous methodologies and data analysis to ensure the accuracy and credibility of the indicators, thereby reflecting the true state of ecological efficiency.

Furthermore, recognizing the multidimensional nature of ecological efficiency, the indicator system encompasses a broad range of metrics across economic, environmental, and social dimensions, ensuring its comprehensiveness for assessing the overall development of ecological efficiency. Finally, the study selects key indicators that adequately represent the development of ecological efficiency, ensuring the representativeness and reliability of the evaluation results. The adjusted comprehensive ecological efficiency evaluation system includes five primary indicators—resource utilization, growth quality, green development, environmental governance, and ecological protection—along with 29 secondary indicators, such as total energy consumption, per capita GDP, park green space area, centralized sewage treatment rate, and forest stock volume, as shown in Table 1.

Table 1. Ecological Efficiency Evaluation Indicator System.

Primary Indicator	No.	Secondary Indicator	Unit	Indicator Type	Weight (%)
Resource Utilization	1	Total Energy Consumption	Ten thousand tons of standard coal	−	3.57
	2	Total Water Consumption	Tons per 100 million yuan	−	3.57
	3	Energy Consumption per Unit GDP	Tons of standard coal per 10,000 yuan	−	3.57
	4	Electricity Consumption per Unit GDP	kWh per yuan	−	3.59
	5	Arable Land Retention	Square kilometers	−	3.59
	6	Construction Land Area	Square kilometers	−	3.62
Growth Quality	7	Per Capita GDP	10,000 yuan per person	+	3.46
	8	Per Capita Disposable Income	10,000 yuan	+	3.46
	9	Proportion of the Tertiary Industry in GDP	%	+	3.53
	10	Proportion of Import and Export in GDP	%	+	3.32
	11	Proportion of Technology Market Transactions in GDP	%	+	3.04
	12	Proportion of R&D Expenditure in GDP	%	+	3.11
	13	Total Output of Environmental Protection Enterprises	100 million yuan	+	3.39
Green Development	14	Park Green Space Area	Square kilometers	+	3.41
	15	Green Coverage Rate of Built-up Areas	%	+	3.58
	16	Public Transport Passenger Volume per 10,000 People	Ten thousand passengers per 10,000 people	+	3.39
	17	Sulfur Dioxide Emissions	Ten thousand tons	−	3.59
	18	Ammonia Nitrogen Emissions	Ten thousand tons	−	3.59
Environmental Governance	19	Centralized Sewage Treatment Rate	%	+	3.6
	20	Municipal Solid Waste Treatment Rate	%	+	3.6
	21	Forestry Protection Investment	100 million yuan	+	3.34
	22	Environmental Monitoring Investment	100 million yuan	+	3.31
	23	Comprehensive Utilization Rate of Industrial Solid Waste	%	+	3.54
	24	Proportion of Environmental Pollution Control Investment in GDP	%	+	3.52
	25	Proportion of Energy Saving and Environmental Protection Expenditures in Total Fiscal Expenditure	%	+	3.53
Ecological Protection	26	Forest Stock Volume	100 million cubic meters	+	3.24
	27	Forest Coverage Rate	%	+	3.48
	28	Total Afforestation Area	Square kilometers	+	3.42
	29	Nature Reserve Area	Square kilometers	+	3.04

Considering data availability, the study collects representative data on ecological efficiency development for 30 provinces in mainland China (excluding Tibet) from 2013 to 2021 as the basis for the analysis. The data are sourced from the China Statistical Yearbook as well as the statistical yearbooks and bulletins of provincial and municipal government departments.

2.2. Measurement of Ecological Efficiency Levels

Building upon data collection and processing, this study employs the entropy method to calculate the weights of various indicators. The entropy method is grounded in the information content inherent in the indicators, utilizing the calculation of the information entropy to determine the degree of dispersion of each indicator. Compared with subjective weighting approaches such as the analytic hierarchy process, the entropy method minimizes human bias and objectively derives weights based on the variability of each indicator, making it particularly suitable for multi-dimensional ecological efficiency assessments. Following the standardization of the indicators, this study utilizes a composite index method to compute the ecological efficiency index for each province, as represented by the following formula:

$$Z = \sum_{i=1}^{N} W_i Y_i \tag{1}$$

In this equation, Z represents the ecological efficiency development index, Y denotes the dimensionless values of the indicators, W refers to the weights of the indicators, and N is the total number of indicators. This integrated approach allows the ecological efficiency performance of each province to be expressed as a single comparable index, reflecting the combined contribution of economic, environmental, and resource-use dimensions.

2.3. Theil Index

The Theil index is a commonly used measure of inequality that can assess the degree of disparity in ecological efficiency across different regions, serving as an indicator of both the fairness and sustainability of ecological efficiency. The advantage of the Theil index lies in its ability to decompose overall regional inequality into within-region and between-region differences, thereby facilitating an examination of their respective impacts and contributions to the total disparity in the study units. This decomposition feature is particularly important in a geographically large and economically diverse country like China, where regional disparities may stem from fundamentally different economic structures and development trajectories. This study employs the Theil index to quantitatively assess the ecological efficiency disparities among different regions, measuring the regional variation in ecological efficiency at the provincial level. This approach contributes to enhancing the sustainability of social ecological efficiency, ensuring a fair distribution of resources and benefits, and fostering the coordinated development of the economy, environment, and society. The specific formula is as follows:

$$T = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{S_i}{u}\right) \ln \left(\frac{S_i}{u}\right) \tag{2}$$

In this equation, T represents the Theil index of the comprehensive ecological efficiency score for China, S_i denotes the green development score of province i, and μ is the mean ecological efficiency score for the 30 provinces.

By decomposing the Theil index, we can separately measure within-region and between-region disparities, with the following calculation formulas:

$$T_w = \sum_{j=1}^{m} f_i \frac{u_j}{u} T_j \tag{3}$$

$$T_j = \frac{1}{n} \sum_{i=1}^{n} \frac{T_{ij}}{u_j} \ln \frac{T_{ij}}{u_j} \tag{4}$$

$$T_b = \sum_{j=1}^{m} f_i \frac{u_j}{u} \ln \frac{u_j}{u} \tag{5}$$

In these equations, $T = T_w + T_b$, where T_w represents the within-region disparity, and T_b represents the between-region disparity. T_j denotes the Theil index for region j, f_j is the proportion of the number of provinces within region j relative to the total number of provinces, u_j is the mean ecological efficiency score for region j, and T_{ij} is the ecological efficiency score for province i within region j. As such, the Theil index not only provides a numerical representation of overall inequality but also helps identify whether disparities are primarily driven by internal regional heterogeneity or cross-regional differences, offering deeper insights into the structural sources of ecological efficiency variation.

2.4. Exploratory Spatial Analysis

To investigate the spatial correlation characteristics of ecological efficiency levels across Chinese provinces, this study employs Geoda and ArcGIS for spatial autocorrelation testing. Spatial autocorrelation effectively reflects the spatial disparities in ecological efficiency levels between different regions, including both global and local spatial autocorrelation. Spatial autocorrelation analysis is critical because ecological efficiency is strongly influenced by geographic proximity, regional spillover effects, and policy diffusion, making it necessary to examine not only provincial performance but also the broader spatial structure. The specific formulas are as follows:

$$\textit{Moran' } I = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} \left(Y_i - \overline{Y}\right) \left(Y_j - \overline{Y}\right)}{S^2 \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}} \tag{6}$$

$$I_i = \frac{\sum_{j \neq 1}^{n} W_{ij} \left(Y_i - \overline{Y}\right) \left(Y_j - \overline{Y}\right)}{S^2} \tag{7}$$

In these equations, W_{ij} represents the spatial weight matrix, where adjacent provinces are assigned a value of 1, and non-adjacent provinces are assigned a value of 0.

Both the global and local Moran's indices range from $[-1, 1]$. A value less than 0 indicates a negative spatial correlation in ecological efficiency levels among provinces, while a value greater than 0 suggests a positive correlation. A value of 0 indicates the absence of spatial correlation. Global Moran's I provides an overall measure of spatial clustering across the study area, while Local Moran's I captures local pockets of spatial association, enabling the identification of "high–high" and "low–low" clusters. This dual-level analysis helps uncover both broad regional patterns and localized spatial dynamics.

3. Results and Analysis

3.1. Evaluation and Analysis of Ecological Efficiency Levels

In order to gain a deeper understanding of the temporal evolution and spatial distribution characteristics of ecological efficiency at the provincial level, and to provide an analytical foundation for subsequent research, this study employs a composite index method to calculate the ecological efficiency index. Starting from the perspective of China's traditional regional classification into four major areas, this analysis explores the temporal evolution characteristics of ecological efficiency levels (Figure 1). Such an approach offers a clearer understanding of the disparities in ecological efficiency across different regions and provides a scientific basis for the formulation of targeted policies and measures.

As illustrated in Figure 1, the ecological efficiency levels for the entire nation and the four major regions generally exhibit an upward trend, indicating that concerted efforts in enhancing environmental protection, promoting sustainable development, and fostering green technological innovation have collectively contributed to a significant improvement in ecological efficiency. Over time, the ecological efficiency levels of different regions have gradually converged. From 2012 to 2021, the ecological efficiency levels in the eastern, central, and western regions steadily increased. Notably, the central region made remarkable progress, with its ecological efficiency level rising from the initial lowest point (0.1447) to the highest point (0.7881). This trend reflects the substantial strides made by the central region in improving ecological efficiency, driven primarily by active initiatives and policy support in areas such as environmental protection, sustainable development, and green technological innovation.

Conversely, the northeastern region initially exhibited the highest ecological efficiency level but experienced a noticeable decline in 2016. The region's ecological efficiency showed a fluctuating upward trajectory, indicating that further efforts are needed to enhance environmental protection and ecological efficiency. Strengthening these areas will enable the northeastern region to align with the improvements made in other regions, thus contributing to nationwide ecological efficiency advancements. While the western region has displayed a consistent upward trajectory, its rate of increase has been the slowest among the four major regions. In conclusion, to achieve a more balanced and sustainable ecological efficiency nationwide, it is crucial to adopt region-specific strategies to strengthen environmental protection and green technological innovation, thereby further enhancing ecological efficiency across all regions.

3.2. Spatial Visualization Analysis of Ecological Efficiency

To more intuitively examine the variation in ecological efficiency indices across provinces, this study employs ArcGIS software to visualize the ecological efficiency measurement results for 30 provinces in China for the years 2012, 2015, 2018, and 2021. As shown in Figure 2, darker colors represent provinces with higher levels of ecological efficiency. The use of spatial visualization enables a direct comparison of provincial ecological efficiency levels across different years and facilitates the observation of temporal trends in the ecological efficiency index. The results provide valuable insights for formulating policies aimed at enhancing ecological efficiency and promoting sustainable development.

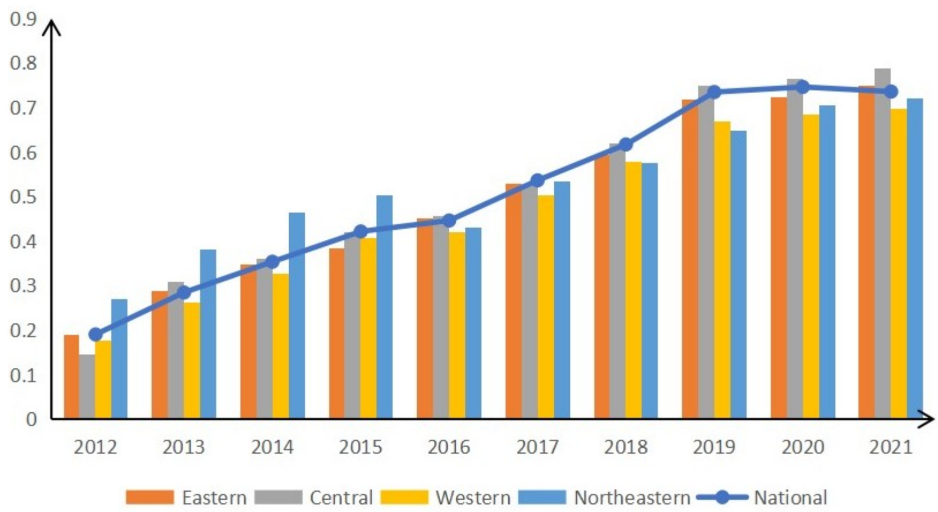
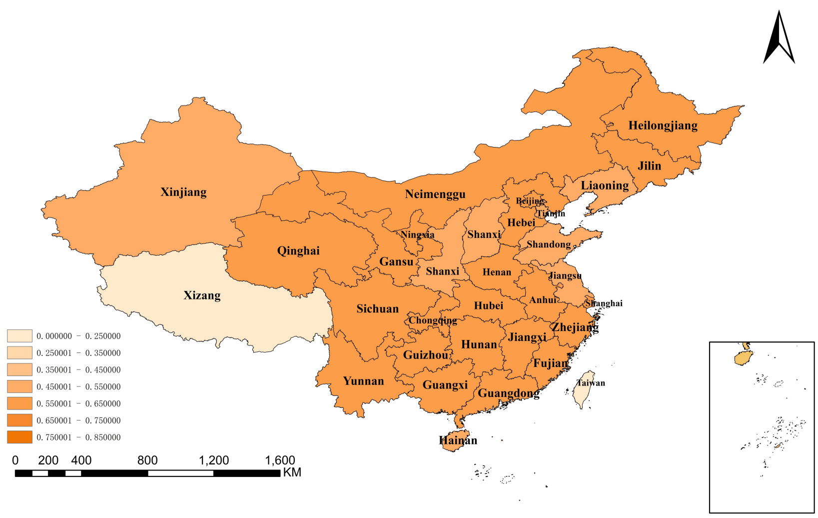


Figure 1. Temporal Evolution of Eco-efficiency Levels Across Various Regions.

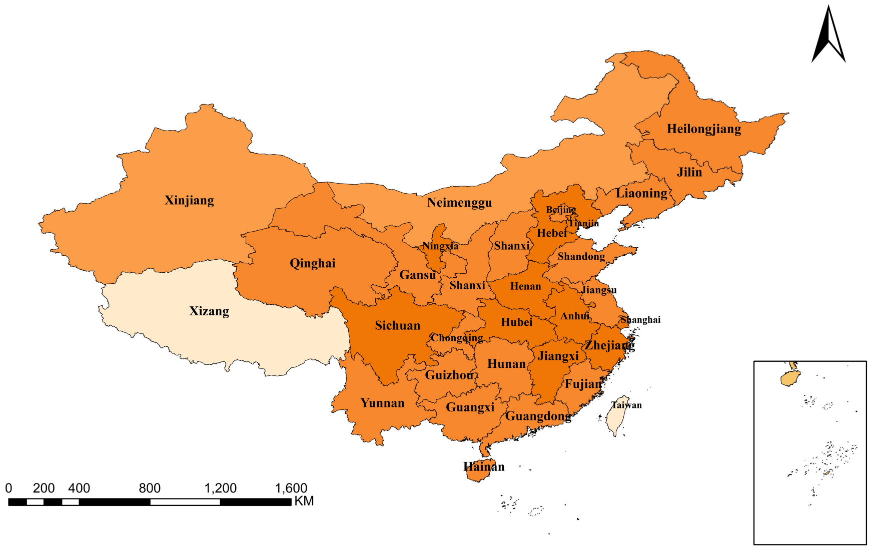
(a) 2012

(b) 2015



(c) 2018

Figure 2. *Cont.*



(d) 2021

Figure 2. Spatial Distribution of Provincial Ecological Efficiency Indices.

By linking the ecological efficiency levels of all provinces, autonomous regions, and municipalities to the provincial vector map data, the visualized results presented in Figure 2 reveal that all provinces achieved notable progress in ecological efficiency during the study period, with a significant overall increase in their indices. In the early years of observation, the ecological efficiency indices across provinces were generally low, indicating relatively weak ecological performance at that time. However, as time progressed, the indices demonstrated a clear upward trajectory, suggesting that the measures and initiatives undertaken by provinces to enhance ecological efficiency have gradually yielded tangible results.

A comparative analysis of changes across provinces further reveals notable regional disparities. Some provinces—particularly Anhui, Zhejiang, and Hebei—exhibited a pronounced rise in ecological efficiency over the study period. This improvement reflects substantial achievements in environmental protection, ecological restoration, and sustainable development, which in turn have injected new momentum into the economic transformation and long-term sustainability of the central and western regions. In contrast, some western provinces, despite beginning from relatively higher initial levels of ecological efficiency, have experienced slower growth, indicating the need for stronger policy and technological interventions to accelerate their ecological progress.

Overall, during the study period, all provinces in China achieved significant improvements in ecological efficiency, with the ecological efficiency indices showing a substantial upward trend. These findings demonstrate the effectiveness of provincial efforts and policy measures aimed at promoting ecological efficiency, underscoring their vital contribution to sustainable development. Nevertheless, the results also highlight disparities in growth rates among regions: the central and eastern regions have advanced rapidly, whereas the western region has progressed more slowly. Therefore, continued and regionally tailored efforts are necessary to further advance ecological efficiency nationwide and promote balanced, sustainable regional development.

3.3. Regional Disparities in Ecological Efficiency Levels

The Theil index, grounded in information theory through the incorporation of entropy concepts, serves as an effective analytical tool for examining regional disparities. This study employs the Theil index to analyze the regional differences in ecological efficiency levels across China. Based on the formulas presented in Section 2.3, the Theil index values of China's ecological efficiency levels from 2012 to 2021 are calculated and further decomposed into within-region and between-region disparities, as shown in Table 2.

As observed from the table, the overall provincial disparities in China's ecological efficiency levels demonstrate a marked downward trend from 2012 to 2021, with a substantial decline in magnitude. Specifically, the Theil index decreased from 0.0263 to 0.0026—a reduction of approximately 90 percent. This result indicates that China's provinces have achieved significant progress in improving ecological efficiency, with inter-provincial disparities narrowing considerably and regional equity improving substantially. This convergence can largely be attributed to the Chinese government's strong emphasis on ecological efficiency, reflected in a series of policy initiatives aimed at promoting the development of green industries, enhancing resource utilization efficiency, and improving environmental quality.

Table 2. Theil Index of China's Eco-efficiency Levels (2012–2021).

Year	Overall Disparity	Inter-Regional Disparity	Intra-Regional Disparity				
			Overall	Eastern	Central	Western	Northeastern
2012	0.0263	0.0060	0.0203	0.0334	0.0078	0.0178	0.0091
2013	0.0110	0.0010	0.0100	0.0131	0.0082	0.0076	0.0119
2014	0.0063	0.0018	0.0045	0.0059	0.0015	0.0051	0.0037
2015	0.0063	0.0017	0.0046	0.0053	0.0046	0.0047	0.0022
2016	0.0045	0.0002	0.0043	0.0021	0.0034	0.0051	0.0106
2017	0.0026	0.0003	0.0022	0.0017	0.0041	0.0017	0.0025
2018	0.0018	0.0000	0.0018	0.0022	0.0014	0.0016	0.0019
2019	0.0028	0.0002	0.0025	0.0032	0.0018	0.0026	0.0012
2020	0.0027	0.0004	0.0023	0.0025	0.0013	0.0028	0.0018
2021	0.0026	0.0007	0.0019	0.0015	0.0005	0.0034	0.0008

However, after 2018, the Theil index experienced a moderate increase and stabilized around 0.0027, suggesting a slight widening of ecological efficiency disparities. This pattern implies that the progress of ecological efficiency in certain provinces may have stagnated or fallen behind relative to others. From 2012 to 2020, both within-region and between-region disparities declined significantly, displaying a similarly pronounced downward trajectory. The within-region disparity fell from 0.0203 to 0.0019, representing a 90 percent reduction, while the between-region disparity decreased even more sharply—by approximately 93 percent.

3.4. Regional Decomposition of Intra- and Inter-Regional Disparities

An examination of the decomposition results for within-region disparities reveals that the Theil index among provinces in the eastern region remains relatively high, indicating considerable heterogeneity within the region. However, over time, the Theil index in the east has declined substantially, reaching a relatively balanced level by 2021. Both the central and northeastern regions exhibit clear downward trends in their Theil indices, with both attaining relatively low levels. Although the overall regional disparities show a general decline, the western region displays notable volatility in its Theil index, which shows an upward trajectory between 2017 and 2021. This fluctuation can be largely attributed to the western region's relative economic underdevelopment, limited resource endowments, and significant environmental pressures, all of which pose greater challenges for improving ecological efficiency and contribute to higher variability in the Theil index.

In summary, China's provincial ecological efficiency levels are generally high, with overall disparities remaining small. Nevertheless, the western region exhibits more pronounced fluctuations in ecological efficiency disparities, highlighting the need for enhanced policy support and financial investment to promote balanced ecological efficiency nationwide.

To further understand the contribution of intra- and inter-regional disparities to China's provincial ecological efficiency differences, this study calculates the contribution rates of disparities from 2012 to 2021 using the formulas presented in Section 2.3, as shown in Table 3. The results indicate that intra-regional disparities accounted for more than 50 percent of the total differences during 2012—2021, suggesting that the overall disparities in China's ecological efficiency primarily stem from within-region differences. This can be explained by China's vast geographic expanse, where variations in natural resource endowments, environmental conditions, and levels of economic development among provinces jointly contribute to differences in ecological efficiency across regions.

From 2012 to 2021, the average contribution rates of ecological efficiency disparities in the eastern, central, western, and northeastern regions were 0.3094, 0.1261, 0.3242, and 0.0840, respectively. The pronounced disparities in the eastern and western regions may be associated with challenges related to industrial restructuring, economic transformation, and resource constraints. Meanwhile, the more balanced performance of the central and northeastern regions demonstrates their meaningful contributions to the overall improvement of national ecological efficiency.

To achieve greater equilibrium in ecological efficiency nationwide, it is essential to strengthen policy support and financial investment in both the eastern and western regions, while continuing to consolidate the progress made in the central and northeastern regions. Such coordinated efforts will help advance ecological efficiency comprehensively across the entire country.

3.5. Spatial Correlation Analysis of Ecological Efficiency Levels

To examine the overall spatial correlation of ecological efficiency levels across China's provinces, this study constructs a spatial weight matrix and analyzes the spatial interdependence among regions, with the aim of exploring how regional linkages influence ecological efficiency levels. The Global Moran's I index is employed to measure the overall spatial correlation of ecological efficiency across provinces, and the results are presented in Table 4.

Table 3. Contribution Rate of Intra-regional and Inter-regional Disparities to China's Eco-efficiency Levels (2012–2021).

Year	Intra-Regional Disparity Contribution Rate (%)					Inter-Regional Disparity Contribution Rate (%)
	Overall	Eastern	Central	Western	Northeastern	
2012	0.7707	0.4153	0.0479	0.2692	0.0383	0.2289
2013	0.9099	0.3899	0.1417	0.2579	0.1208	0.0901
2014	0.7129	0.3069	0.0472	0.2902	0.0697	0.2871
2015	0.7234	0.2688	0.1383	0.2758	0.0402	0.2766
2016	0.9575	0.1628	0.1453	0.4177	0.2314	0.0425
2017	0.8706	0.2256	0.3081	0.2367	0.1010	0.1294
2018	0.9944	0.4160	0.1564	0.3185	0.1027	0.0056
2019	0.9130	0.3926	0.1335	0.3453	0.0404	0.0870
2020	0.8550	0.3157	0.1011	0.3715	0.0653	0.1450
2021	0.7326	0.2000	0.0413	0.4590	0.0305	0.2713

Table 4. Measurement Results of Spatial Correlation in Provincial Ecological Efficiency Levels.

Year	*Moran's I*	*P*	Year	*Moran's I*	*P*
2012	0.118	0.035	2017	0.064	0.085
2013	−0.054	0.428	2018	−0.033	0.047
2014	0.108	0.031	2019	0.055	0.098
2015	0.066	0.081	2020	−0.004	0.296
2016	0.014	0.207	2021	0.028	0.225

According to the results shown in Table 4, during six years—2012, 2014–2015, and 2017–2019—the calculated ecological efficiency levels pass the significance tests. In these years, the Moran's *I* indices are positive, and the corresponding *p*-values are less than 0.1, indicating that the ecological efficiency levels exhibit significant spatial autocorrelation characterized by positive spatial clustering. In contrast, for the remaining four years, the *p*-values exceed 0.1, suggesting that the results are not statistically significant. This implies that in those years, ecological efficiency levels did not demonstrate a clear spatial autocorrelation pattern, and the spatial distribution of ecological efficiency was relatively irregular.

3.6. Local Spatial Autocorrelation Analysis of Ecological Efficiency

While the global Moran's *I* index effectively reveals the overall spatial correlation of ecological efficiency, it does not provide insight into the specific clustering patterns of ecological efficiency at the provincial level. Therefore, based on the results of the global Moran's *I* calculations, this study conducts a local spatial autocorrelation analysis to further investigate the spatial clustering characteristics of provincial ecological efficiency levels. The ecological efficiency data for the years 2014, 2017, and 2021 are selected to construct Moran scatter plots (Figure 3), allowing for a more detailed examination of the local spatial patterns of ecological efficiency across provinces.

The results indicate that the slopes of the trend lines for all three years are positive, suggesting a clear spatial clustering effect in provincial ecological efficiency levels. The Moran's *I* values for 2014, 2017, and 2021 are 0.118, 0.064, and 0.028, respectively, confirming the existence of positive spatial correlation across the study period. However, the distribution of scatter points varies across years. In 2014 and 2017, a larger number of provinces are concentrated in the second and third quadrants, while in 2021, the number of provinces located in the first and third quadrants increases. This pattern indicates that an increasing number of provinces exhibit spatial clustering in ecological efficiency—both high–high and low–low clusters are becoming more prominent—and that the positive spatial influence among regions is gradually spreading outward.

3.7. Spatial Clustering Patterns of Ecological Efficiency

Based on the relevant data and scatter plot results, this study further analyzes the spatial clustering characteristics of regional ecological efficiency. Figure 4 provides a clear spatial visualization of the clustering phenomena observed in 2014 and 2021. In the figure, "High–High," "Low–High," "Low–Low," and "High–Low" correspond to the first, second, third, and fourth quadrants of the Moran scatter plot, respectively. Only a subset of regions in each year passed the statistical significance test.

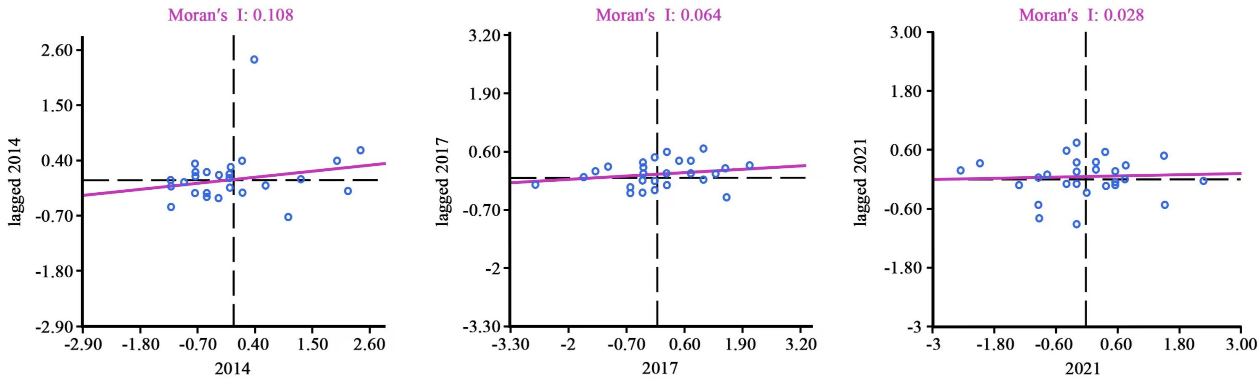


Figure 3. Moran Scatter Plot of Eco-efficiency Levels.

From a regional dynamics perspective, the spatial clustering pattern of provincial ecological efficiency in China has undergone notable changes. In 2014, provinces categorized as “High–High” and “Low–High” clusters were primarily concentrated in the western region, suggesting pronounced intra-regional heterogeneity in ecological and socio-economic efficiency. By 2021, the spatial clustering pattern of provincial ecological efficiency became more distinct, with the central and eastern regions predominantly exhibiting “High–High” clusters, while the western region displayed a prevalence of “Low–Low” clusters. This shift highlights the growing ecological efficiency advantages of the central and eastern regions and their leading role in sustainable development, whereas the western region continues to face challenges due to its relatively slower improvement in ecological efficiency.

At the provincial level, Xinjiang and Gansu initially belonged to the “High–High” cluster, indicating significant ecological efficiency advantages. Xinjiang benefits from vast land resources and abundant natural endowments, while Gansu possesses unique ecological conditions and rich water resources—factors that collectively underpin their higher ecological efficiency levels. In contrast, Shaanxi exhibited a “Low–High” clustering pattern, reflecting comparatively weaker ecological efficiency relative to neighboring provinces. This pattern likely resulted from the influence of adjacent high-efficiency regions such as Xinjiang and Gansu. By 2021, however, major western provinces such as Qinghai and Sichuan had transitioned into the “Low–Low” cluster, suggesting a relative lag in ecological efficiency advancement.

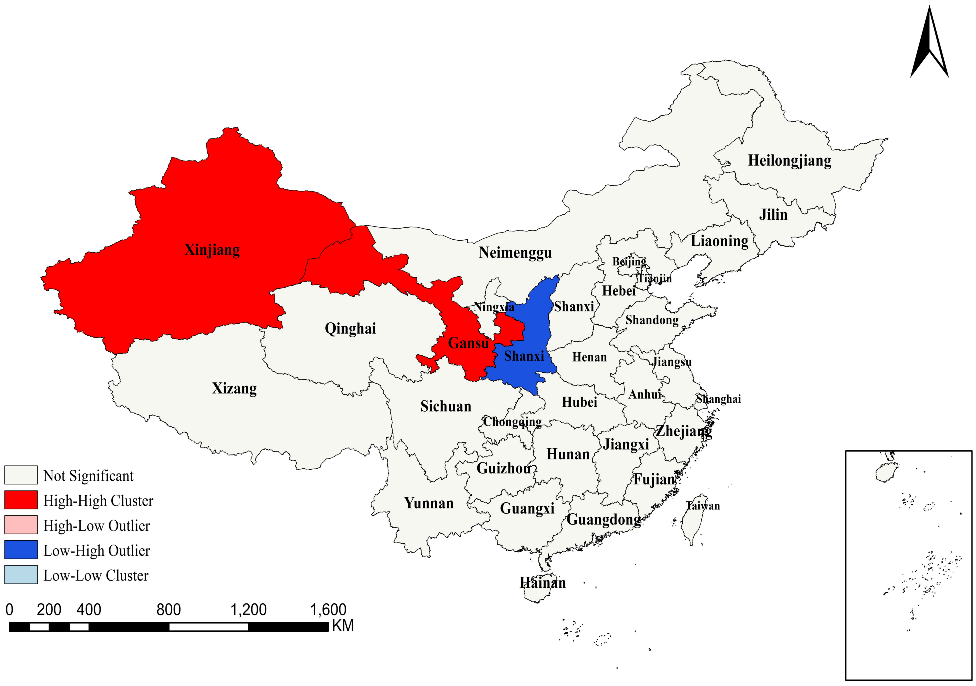
Moreover, “Low–High” cluster provinces show an evident eastward shift over time. The rapid improvement in ecological efficiency in the eastern and northeastern regions has contributed to provinces such as Beijing, Shandong, and Liaoning evolving into “High–High” clusters, while neighboring regions such as Inner Mongolia and Jilin have emerged as “Low–High” provinces.

Overall, the spatial autocorrelation of China’s provincial ecological efficiency levels remains irregular but demonstrates evident clustering tendencies. These clusters are primarily characterized by high-value and low-value agglomerations, revealing an expanding scope of positive spatial association and an increasingly differentiated spatial structure of ecological efficiency across provinces.

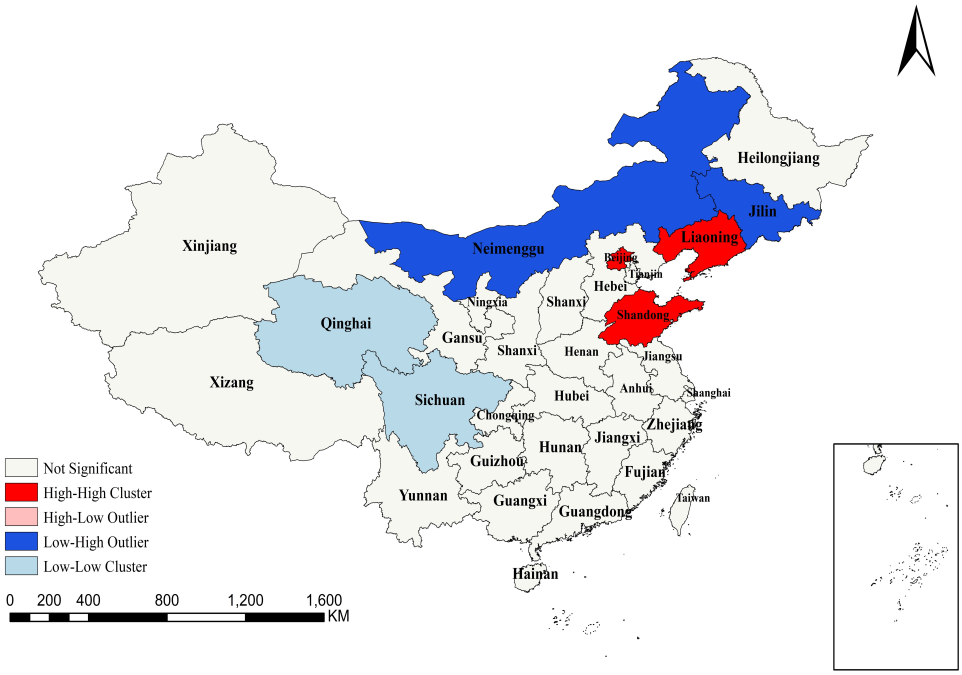
4. Conclusions and Recommendations

Drawing on panel data from 30 provincial-level administrative units in China, this study constructs an ecological efficiency evaluation system encompassing five dimensions: resource utilization, growth quality, green development, environmental governance, and ecological protection. Using a comprehensive evaluation model, it measures the ecological efficiency levels of each province from 2012 to 2021. Combined with the Theil index and spatial autocorrelation analyses, the study systematically reveals the spatiotemporal evolution and regional disparities of ecological efficiency across China’s provinces.

The results indicate that provincial ecological efficiency in China exhibited a significant upward trajectory from 2012 to 2021, reflecting the progressive effectiveness of national policies in ecological civilization construction, energy structure transformation, and green technological innovation. Among the regions, the central provinces demonstrated the most remarkable improvement, rising from initially low levels to relatively high levels of ecological efficiency—highlighting the synergistic effects of policy support and industrial transformation. The eastern region maintained consistently high ecological efficiency, underscoring its leading role in technological innovation and green governance. Although the western region showed continuous improvement, its growth rate remained comparatively modest, constrained by industrial structure and resource endowment disparities. Meanwhile, the northeastern region, after experiencing periodic fluctuations, began to recover, suggesting that regional revitalization policies have exerted a positive influence on ecological performance. Overall, China’s provincial ecological efficiency has shown a clear pattern of regional convergence, with interregional coordination and balance improving steadily over time. Compared with previous studies, which often reported persistent or widening regional disparities in ecological efficiency, our findings reveal a more pronounced trend of regional convergence, highlighting recent policy impacts that earlier research did not fully capture.



(a) 2014



(b) 2021

Figure 4. LISA Cluster Map of Eco-efficiency Levels.

Further decomposition of regional disparities reveals that from 2012 to 2021, the overall gap in provincial ecological efficiency in China exhibited a clear downward trend. The Theil index declined from 0.0263 to 0.0026, representing a remarkable reduction of approximately 90 percent, which indicates a growing convergence in ecological efficiency across provinces. However, a modest rebound occurred after 2018, suggesting that improvements in ecological efficiency have stagnated in certain regions and that underlying imbalances in coordinated regional development persist.

In terms of the sources of disparity, intra-regional differences remain the primary contributors to the overall gap. Among them, the eastern and western regions display relatively large internal disparities, while the central and northeastern regions are more balanced. This pattern underscores the significant variations that still exist within regions in terms of economic structural adjustment, environmental governance intensity, and green innovation capacity. The persistence of such internal heterogeneity has become a key constraint on the overall enhancement of national ecological efficiency.

Spatial analysis results further illuminate the clustering patterns of provincial ecological efficiency. The Global Moran's *I* indices are positive and statistically significant in multiple years, indicating a strong positive spatial autocorrelation across China's provinces. The local spatial autocorrelation analysis reveals a stable "High–High" clustering pattern in the central and eastern regions, contrasted with a typical "Low–Low" clustering in the western region. This spatial configuration reflects a pronounced regional lock-in effect in ecological efficiency. On one hand, high-efficiency regions benefit from technology spillovers and policy demonstration effects that reinforce their leading positions. On the other hand, low-efficiency regions face persistent disadvantages arising from weaker resource endowments, limited infrastructure, and insufficient policy support. Overall, China's spatial structure of ecological efficiency has gradually evolved toward stability, yet regional development gradients and path dependence continue to shape the spatial dynamics of ecological efficiency across provinces. These findings underscore the strategic importance of addressing spatial dependence and regional lock-in effects in the design of ecological governance policies. Moreover, the observed spatial patterns highlight the need for differentiated regional strategies to strengthen interregional linkages and maximize the spillover benefits of high-efficiency regions.

The findings of this study offer several important insights for promoting China's green and high-quality development. First, the continuous enhancement of ecological efficiency represents a crucial pathway for achieving the nation's dual-carbon goals and fostering coordinated regional development. Each region should formulate differentiated policies tailored to its resource endowments and industrial base. The eastern region should continue to leverage its institutional and technological advantages by strengthening green technology diffusion and innovation leadership. The central region, situated at a critical juncture of industrial transformation, should capitalize on this opportunity by introducing green finance instruments and clean energy technologies to improve resource utilization efficiency. Meanwhile, the western region should expand ecological compensation mechanisms and increase public investment to build an eco-friendly industrial system, thereby narrowing intra-regional disparities. At the macro level, national policymakers should reinforce cross-regional coordination mechanisms and promote the construction of unified carbon markets and ecological compensation frameworks. At the micro level, enterprises should enhance green technological innovation and adopt cleaner production modes, while households and communities should be encouraged to participate in green consumption and low-carbon lifestyles.

Second, the national ecological governance framework should be further optimized to enhance interregional coordination and strengthen the institutional foundation for ecological compensation. Policy tools such as fiscal transfer payments, carbon trading markets, and green credit systems should be more effectively utilized to promote the synergistic improvement of ecological efficiency across regions. Moreover, it is imperative to refine the green technology innovation system, accelerate the green transformation of energy-intensive industries, and enhance the technological underpinnings of ecological efficiency improvement.

Overall, this study systematically uncovers the spatiotemporal evolution and spatial clustering patterns of China's provincial ecological efficiency. Theoretically, it enriches the analytical framework of ecological efficiency and spatial econometrics; practically, it provides valuable policy guidance for formulating regionally differentiated green development strategies. Nevertheless, several limitations remain. On one hand, due to data availability constraints, certain indicators may not fully capture the dynamic evolution of ecological efficiency. On the other hand, this study does not yet empirically examine the determinants of ecological efficiency. Future research could employ spatial econometric models to further explore the mechanisms through which technological innovation, industrial restructuring, and environmental regulation influence ecological efficiency. Additionally, subsequent studies could incorporate higher-resolution datasets, such as prefectural or enterprise-level data, to better capture intraregional heterogeneity and dynamic adjustment mechanisms. Future research may also explore scenario-based simulations or machine learning approaches to more accurately predict spatial evolution trends under different policy pathways.

In summary, this study underscores the strategic importance of enhancing regional ecological efficiency in the context of China's "carbon peaking and carbon neutrality" goals. Looking forward, achieving the dual objectives of ecological efficiency improvement and balanced regional development will require an integrated approach that combines dynamic analysis with practical policy implementation.

Author Contributions

Z.W.: Conceptualization, Methodology, Data Curation, Writing. X.Z.: Formal Analysis, Visualization, Validation. H.Y.: Investigation, Resources, Editing. Q.Z.: Supervision, Writing—Review & Editing, Project Administration. All authors have read and agreed to the published version of the manuscript.

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The data presented in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

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Use of AI and AI-Assisted Technologies

No AI or AI-assisted technologies were used in the writing or analysis of this manuscript.

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