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Original Research

Coupling Coordination and Regional Disparities: Analyzing the Interaction between Digital Economy Development and Ecological Environment Quality in China (2011-2021)

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Abstract

This study quantitatively analyzes the coupling and collaborative relationship between digital economy development and ecological environment quality across China's provinces from 2011 to 2021. By employing the coupling coordination degree, decoupling index, and Theil index, the research evaluates the strength and dynamics of this relationship, revealing significant regional disparities and evolving trends. The analysis shows that while the eastern region exhibits a relatively high level of digital economy development with notable internal variation, the central region has shown gradual improvements in coordination. The western region, despite progress, still requires further enhancement. Specifically, provinces like Beijing and Tianjin struggle to balance digital economy growth and ecological sustainability, whereas Jiangsu and Zhejiang have achieved a better synergy. The decoupling index reveals that regions such as Tianjin and Hebei have successfully decoupled economic growth from environmental degradation, while Shanxi and Inner Mongolia exhibit weak negative decoupling, underscoring the need for enhanced environmental protection efforts. Nationally, the coupling coordination degree generally trends upward, though a slight decline in 2021 indicates ongoing challenges in achieving sustainable regional development. Policy recommendations include increasing investment and policy support in the central and western regions, promoting green development, improving ecological environment quality, and fostering interregional cooperation to achieve balanced and sustainable development. This study provides valuable insights for regional policy-making aimed at harmonizing digital economy development with ecological sustainability.

Keywords: digital economy, ecological environment quality, coupling coordination degree, decoupling index, Theil index

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Introduction

The "14th Five-Year" Digital Economy Development Plan [1] emphasizes that the digital economy, as the primary economic form of our era, is driving unprecedented transformations [2, 3]. Its extensive reach and rapid growth profoundly influence current social production, lifestyle, and governance methods, becoming a critical force in reshaping global resources, restructuring the economic framework, and altering competitive dynamics [4, 5]. According to the "China Digital Economy Development Report," the scale of China's digital economy surpassed 50 trillion yuan in 2022, accounting for 41.5% of GDP [6, 7]. The "2023 Government Work Report" further emphasized the digital economy, while the "2035 Vision Outline" signaled favorable policies to promote its development, underscoring its role as a backbone of national modernization [8, 9].

Theoretically, the relationship between the digital economy and ecological environment quality is multifaceted and complex. The digital economy can positively impact the environment through improving resource allocation, enhancing energy efficiency, and promoting green technology development [10-12]. However, it also poses challenges such as increased electronic waste, higher energy consumption, and potential pollution from digital infrastructure [13-15]. Previous studies have shown that digital technologies, like big data and the Internet of Things (IoT), can facilitate better environmental monitoring and management, helping to mitigate environmental degradation [16, 17]. Conversely, the rapid expansion of data centers and the widespread use of electronic devices contribute significantly to carbon emissions and electronic waste, which can negatively impact ecological resilience [18]. Therefore, it is crucial to understand under what conditions the digital economy can support ecological sustainability rather than hinder it.

The concept of the digital economy originates from Stiegler's information economy [19], and Tapscott first introduced the term "digital economy" in 1996 [20], describing it as an economic system transformed by the widespread application of digital technology, leading to changes in the economic environment and activities. With contributions from various scholars, the focus of research has shifted from emphasizing digital technology to its economic effects [21, 22]. As the internet and communication industries merged, the digital economy matured. The G20 Summit officially interpreted the digital economy, highlighting digital knowledge and information as key production factors [23-25].

A comprehensive literature review indicates that the impact of the digital economy on ecological environment quality is influenced by multiple factors, including technological advancements, policy frameworks, and regional economic structures [26, 27]. For instance, the adoption of digital technologies in industrial processes can lead to significant reductions in energy consumption and emissions [28]. On the other hand, the lack of adequate regulations and policies may result in increased electronic waste and environmental degradation. Factors such as digital infrastructure, innovation capacity, and economic development levels also play a critical role in determining the net environmental impact of the digital economy [29]. These findings underscore the need for a nuanced approach to assess the digital economy's dual role in both enhancing and challenging ecological sustainability.

The rapid development of the digital economy has brought comprehensive changes to production, lifestyle, and governance methods, presenting both opportunities and challenges to the ecological environment [30, 31]. On the one hand, the digital economy significantly promotes the conversion of new and old growth drivers, effectively driving industrial upgrading [32, 33] and benefiting environmental protection. On the other hand, its growth leads to increased electronic waste [34] and electricity consumption [35], negatively impacting the ecological environment [36, 37]. According to "China's Decarbonization Path for Digital Infrastructure: Carbon Reduction Potential and Challenges for Data Centers and 5G (2020-2035) [38]," by 2035, the total electricity consumption of China's data centers and 5G will be 2.5-3 times that of 2020, reaching 695.1-782 billion kWh, accounting for 5%-7% of total social electricity consumption. The total carbon dioxide emissions will be 230-310 million tons, accounting for 2%-4% of the national total [39]. While digital technology brings great convenience, it also expands energy consumption and pollution, posing a significant challenge.

Therefore, pressing issues such as "Can and how can the digital economy and ecological environment achieve coordinated development?" and "What factors influence the relationship between the two?" need urgent resolution. From a theoretical perspective, scholars believe that the digital economy can solve information asymmetry [40, 41], making environmental governance more efficient. Digital technology can improve resource allocation efficiency [42, 43] and reduce resource consumption in traditional production methods [44, 45], thus saving resources and protecting the environment. Conversely, the digital economy might lead to more energy consumption and potential pollution, threatening ecosystem resilience. A good ecological environment and green lifestyle can provide material and talent foundations for the digital economy [46], promoting digital industrialization and industrial digitization.

This study makes several marginal contributions to the existing literature. First, it provides a comprehensive analysis of the coupling relationship between digital economy development and ecological environment quality across 31 Chinese provinces over a decade, which has not been systematically explored in previous studies. Second, by integrating the coupling coordination degree, decoupling index, and Theil index, this research offers a novel methodological framework for assessing regional

Table 1. Evaluation System for Digital Economy and Ecological Environment.

Primary Indicator	Secondary Indicator	Measurement Indicator	Attribute
Digital Economy	Digital Economy Infrastructure	Proportion of broadband internet users to total population	+
		Proportion of mobile phone users to total population	+
	Digital Industrialization	Information transmission, computer services, and the software industry as a proportion of the total population	+
		Per capita telecommunications business revenue	+
	Industrial Digitalization	Peking University Inclusive Finance Index	+
Ecological Environment	Ecological Environment Level	Proportion of grain planting area to total land area	+
		Green coverage rate in built-up areas	+
	Ecological Environment Pressure	Per capita industrial "three wastes"	-
		Population density	-
	Ecological Environment Response	Comprehensive utilization rate of general industrial solid waste	+
		Centralized treatment rate of sewage treatment plants	+
		Harmless treatment rate of domestic waste	+

disparities and the dynamic interaction between digital and environmental factors. Third, the study presents specific policy implications for achieving balanced and sustainable development, contributing to the ongoing discourse on the digital economy and environmental governance in China.

Methodology and Materials

Research Methods

The Evaluation of the Digital Economy Development Level and Ecological Environment Quality

Based on the "14th Five-Year" Digital Economy Development Plan's elaboration on the digital economy, an evaluation system is established from three dimensions: industrial digitalization, digital industrialization, and digital infrastructure. Indicators are selected based on principles of scientific rigor, comprehensiveness, guidance, and operability. Specific evaluation indicators are detailed in Table 1.

This study utilizes the entropy weight method to comprehensively evaluate the corresponding indicators [47, 48]. The entropy weight method is a statistical technique used to determine the weight of each indicator in a comprehensive evaluation system [49]. Unlike subjective weighting methods, the entropy weight method is based on the degree of variation or disorder among data points. Indicators with greater variability are assigned higher weights, reflecting their relative importance in the evaluation process. This method ensures an objective assessment of the indicators by quantifying the information contained within the data. By applying the entropy weight method, this study objectively determines the influence of each indicator on the overall evaluation of digital economy development and ecological environment quality. Y_{ij} represents the normalized value of the j-th indicator for the i-th object. The contribution of the i-th object under the j-th indicator is calculated as follows:

$$\theta_{ij} = \frac{Y_{ij}}{\sum_{i=1}^{m} Y_{ij}}, i = 1,2,\cdots,m; j = 1,2,\cdots,n.$$

Based on the obtained contribution of H_j, the information entropy of the j-th indicator is calculated as follows:

$$H_j = \left[{}^{-1}/_{\ln(m)}\right] \sum_{i=1}^{m} \theta_{ij} \ln(\theta_{ij}),$$
$$i = 1,2,\cdots,m; j = 1,2,\cdots,n.$$

In the formula, if θ_{ij}=0, it is defined that $\theta_{ij}\ln(\theta_{ij})$=0.

Based on the calculated information using entropy H_j, the entropy weight W_j of each indicator is determined using the following formula:

$$W_j = {}^{(1 - H_j)}\Big/_{\left(n - \sum_{j=1}^{n} H_j\right)}, j = 1,2,\cdots,n.$$

Using the entropy weight W_j and the normalized data Y_{ij}, we can construct the weighted matrix P. The element P_{ij} represents the weighted normalized value of the j-th indicator for the i-th province. The calculation is as follows:

$$P = W_j \times Y_{ij} = \begin{bmatrix} W_1Y_{1,1} & W_2Y_{1,2} & \cdots & W_mY_{1,n} \\ W_1Y_{2,1} & W_2Y_{2,2} & \cdots & W_mY_{2,n} \\ \vdots & \vdots & \vdots & \vdots \\ W_1Y_{m,1} & W_2Y_{m,2} & \cdots & W_mY_{m,n} \end{bmatrix}$$

Using the weighted matrix *P* derived from the entropy weights W_j and normalized data Y_{ij}, we can calculate the comprehensive scores for the digital economy development level and ecological environment quality for each of the 31 provinces over different years.

Tapio Model

The theory of "decoupling" originates from the concept of "decoupling" in physics, initially proposed by the OECD [50]. It refers to breaking the link between "environmental pollution" and "economic goods." The Tapio decoupling model employs an elasticity analysis method based on time spans to derive a decoupling elasticity coefficient, which dynamically reflects the decoupling relationship between variables, making the analysis results more accurate and objective [51, 52]. Based on the decoupling elasticity coefficient method proposed by Tapio in studying the relationship between economic development, transport capacity, and carbon emissions in Europe, this study constructs a corresponding decoupling index model according to the changes between the digital economy development level and ecological environment quality:

$$X_{N,E} = \frac{\Delta N/N}{\Delta E/E}$$

Where $X_{N,E}$ represents the decoupling index between the digital economy development level and ecological environment quality, ΔN represents the difference in the digital economy development level between the current period and the base period. ΔE represents the difference in ecological environment quality between the current period and the base period.

Coupling Coordination Degree Model

The coupling coordination degree model is primarily used to reflect the state of interaction and coordination between two or more systems under the influence of both internal and external factors [53, 54]. This model indicates not only the strength of coupling between systems but also the degree of coordination between them. When both the coupling degree and coordination degree between systems are high, the systems are considered to achieve a benign coupling. The coupling coordination degree model can quantify the coupling coordination degree between the digital economy development level and ecological environment quality in China. The formulas are as follows:

$$C = \left[(N \times E) / \left(\frac{N + E}{2} \right)^2 \right]^{\frac{1}{2}}$$

$$D = C \times T$$

$$T = \alpha N \times \beta E$$

Where N represents the development level of the digital economy. E represents the ecological environment quality. C denotes the coupling degree, indicating the extent of interaction and influence between the systems. T is the comprehensive coordination index, representing the overall development level of the two systems. D is the coupling coordination degree, providing a more comprehensive evaluation of the development status of the two systems. Α and β denote the relative importance of the digital economy development level and ecological environment quality, respectively.

The entropy weight method is utilized to determine the specific values of α\alphaα and β\betaβ. Additionally, following the research of Zeng et al., the coupling coordination degree is classified into four categories (Table 2). Since the numerical ranges of the digital economy development level and ecological environment quality data are inconsistent, this study first normalizes the data before constructing the coupling coordination degree model.

Table 2. Classification of Coupling Coordination Types between the Digital Economy Development Level and Ecological Environment Quality.

Category	Range of D
Low Coordination	(0.0,0.5]
Moderate Coordination	(0.5,0.7]
High Coordination	(0.7,0.9]
Excellent Coordination	[0.9,1.0]

Theil Index

The Theil Index, derived from the concept of entropy in information theory and also known as the Theil Entropy Measure, is widely recognized for its decomposability, which allows for a clear identification of regional disparity structures and sources of differences [55, 56]. This index has been extensively used to analyze regional differences in carbon emissions and energy efficiency [56, 57]. In this study, we introduce the Theil Index to explore the regional disparity characteristics of the coupling degree.

$$T = T_w + T_B$$

$$T_q = \sum_{i=1}^{n_q} \frac{1}{n_q} \left(\frac{d_i}{\overline{d_q}} \right) \ln \left(\frac{d_i}{d_q} \right)$$

$$T_w = \sum_{q=1}^{m} T_q \left(\frac{n_q}{n} \times \frac{\overline{d_q}}{\bar{d}} \right)$$

$$T_B = \sum_{q=1}^{m} \frac{n_q}{n} \left(\frac{\overline{d_q}}{\bar{d}} \right) \ln \frac{\overline{d_q}}{\bar{d}}$$

In the formula, n_q represents the number of provinces included in each region; n is the total number of provinces; T_q is the Theil index of the coupling degree within each region; d_i, $\overline{d_q}$ and $\bar{d}$ denote the coupling degree of province i within each region, the average coupling coordination degree within each region, and the national average coupling coordination degree, respectively; T_w and T_B represent the Theil index within and between regions, respectively. T signifies the overall Theil index of the coupling coordination degree difference, ranging from 0 to 1. A higher T value indicates a greater disparity in the regional coupling coordination degree.

Data Sources

This study utilizes panel data from 31 provinces in China for the years 2011-2021. The primary sources of data include the "China Statistical Yearbook," the "China Regional Economic Statistical Yearbook," and the Digital Inclusive Finance Index published by the Digital Finance Research Center of Peking University. Additional data were sourced from the "China Environmental Statistical Yearbook" [58] and annual water resources statistical bulletins from each province. Missing data were supplemented using interpolation methods. Due to data availability, the research does not cover the regions of Hong Kong, Macau, and Taiwan.

Data Processing

In this study, Excel 2019 software was utilized for basic statistical analysis and processing of the collected data. Graphs and figures were created using Origin 2021 Pro and Adobe Illustrator 2022 software.

Results and Discussion

Temporal and Spatial Changes in China's Digital Economy Development Level

Data from 2011 to 2021 indicate significant differences in the digital economy development levels across Chinese provinces and cities, reflecting the degree and effectiveness of digital transformation in these regions (Fig. 1). Beijing consistently exhibited the highest level of digital economy development throughout the observation period, nearing 1.000 in 2011 and 2012 but experiencing a decline to 0.882 by 2021. Shanghai also showed remarkable performance, with some fluctuations in the early years, but an overall increase from 0.610 in 2011 to 0.721 in 2021. In contrast, Guangdong's digital economy development level showed a declining trend, dropping from 0.486 in 2011 to 0.336 in 2021, indicating challenges in sustaining digital economic growth. Jiangsu and Zhejiang demonstrated continuous progress. Jiangsu's digital economy level grew from 0.338 in 2011 to 0.425 in 2021, while Zhejiang's increased from 0.489 in 2011 to 0.503 in 2021, reflecting successful digital transformation efforts. Hainan and Chongqing also showed significant improvement, with Hainan increasing from 0.238 in 2011 to 0.306 in 2021 and Chongqing from 0.171 to 0.240 during the same period.

Several provinces in Northeast and Western China exhibited lower levels of digital economy development. Heilongjiang experienced significant fluctuations and an overall decline, from 0.157 in 2011 to 0.091 in 2021. Jilin's digital economy development level continuously decreased from 0.214 in 2011 to 0.101 in 2021. Regions such as Henan, Hunan, and Guangxi showed moderate improvements, with Henan's level rising from 0.059 in 2011 to 0.168 in 2021, reflecting gradual progress. Guizhou and Yunnan displayed more volatility, with Guizhou peaking at 0.136 in 2017 but dropping to 0.081 by 2021. Nationally, the average digital economy development level showed slight fluctuations, starting at 0.234 in 2011, peaking at 0.253 in 2020, and slightly decreasing to 0.252 in 2021. This overall stability masks regional disparities, highlighting the need for targeted policies to bridge the digital divide.

The analysis indicates significant urban-rural disparities in China's digital economy development [59]. Major cities like Beijing and Shanghai lead in digital economic development, while rural and less developed regions lag significantly. This urban-rural gap necessitates strategic investments in digital infrastructure and education in underdeveloped areas to bridge the divide. The continuous progress in Jiangsu and Zhejiang demonstrates the effectiveness of their digital policies and investments. These regions can serve as benchmarks for other provinces aiming to enhance their digital economy levels. The decline in development levels in northeast provinces such as Heilongjiang and Jilin, along with the volatility in western provinces like Guizhou and Yunnan, suggests that these regions face structural challenges requiring comprehensive regional development strategies.

To promote balanced digital economy development, policies should focus on strengthening digital infrastructure in lagging regions, improving digital literacy, and encouraging innovation and entrepreneurship [60, 61]. Additionally, cross-regional

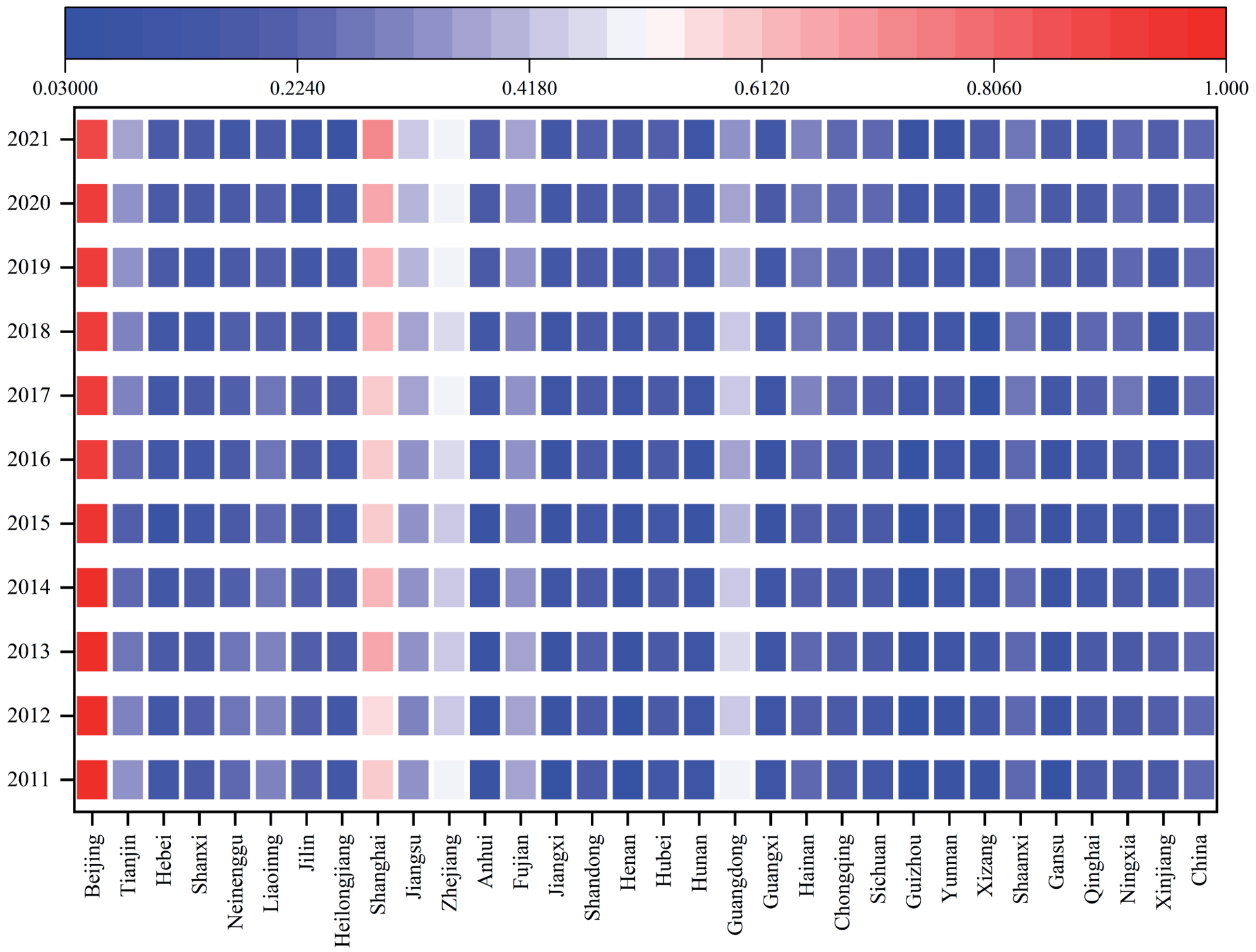

Fig. 1. Digital Economy Development Levels in China (2011-2021).

cooperation and knowledge transfer from leading regions can help accelerate digital transformation nationwide. While positive trends are evident in several regions, significant disparities persist. Addressing these disparities through targeted and inclusive policies is crucial for achieving balanced and sustainable digital growth across China.

Comprehensive Evaluation of Ecological Environment Quality in China

Data from 2011 to 2021 indicate significant differences in the ecological environment quality across Chinese provinces and cities, reflecting the progress and challenges in environmental protection and governance in different regions (Fig. 2). Inner Mongolia, Heilongjiang, and Guangxi have shown outstanding performance in terms of ecological environment quality. Inner Mongolia maintained a high level of ecological environment quality throughout the observation period. Heilongjiang's quality increased from 0.575 in 2011 to 0.630 in 2020, while Guangxi's improved from 0.515 in 2011 to 0.547 in 2020. Fujian and Jiangxi also showed continuous improvement in the quality of the ecological environment. Fujian's quality increased from 0.519 in 2011 to 0.530 in 2020, and Jiangxi's from 0.530 in 2011 to 0.533 in 2020. Zhejiang and Hainan experienced significant enhancements, with Zhejiang's quality rising from 0.469 in 2011 to 0.473 in 2020 and Hainan's from 0.506 in 2011 to 0.508 in 2020. Sichuan, Guizhou, and Yunnan also displayed positive trends. Sichuan's quality increased from 0.415 in 2011 to 0.398 in 2020, Guizhou's from 0.441 in 2011 to 0.500 in 2020, and Yunnan's from 0.515 in 2011 to 0.549 in 2020.

However, some provinces, such as Beijing, Tianjin, Hebei, and Shanxi, performed poorly in terms of ecological environment quality. These regions exhibited significant fluctuations and generally low levels during the observation period: Beijing's ecological environment quality dropped from 0.319 in 2011 to 0.188 in 2021. Tianjin's quality decreased from 0.269 in 2011 to 0.078 in 2021. Hebei's quality declined from 0.366 in 2011 to 0.170 in 2021. Shanxi's quality fell from 0.319 in 2011 to 0.139 in 2021. Shanghai and Jiangsu also showed weaker performance: Shanghai's ecological environment quality decreased from 0.279 in 2011 to 0.090 in 2021, and Jiangsu's quality declined from 0.308 in 2011 to 0.129 in 2021.

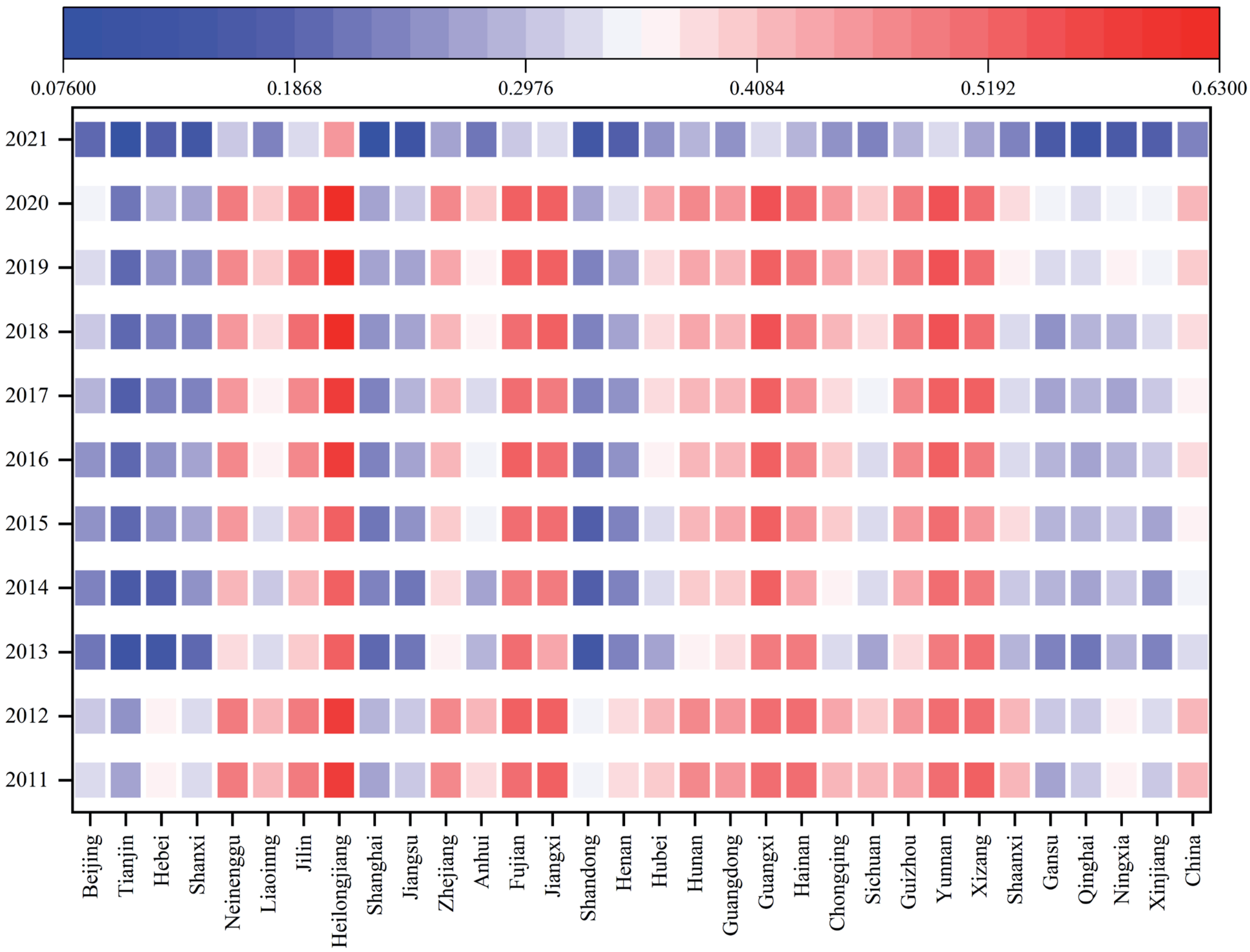

Fig. 2. Ecological Environment Quality in China (2011-2021).

Nationally, the average ecological environment quality showed slight fluctuations, starting at 0.412 in 2011, peaking at 0.413 in 2020, and dropping to 0.232 in 2021. These data reflect the progress and challenges in ecological environment governance across the country and highlight significant regional differences in environmental protection. Overall, there are notable regional disparities in the ecological environment quality of China. Regions such as Inner Mongolia, Heilongjiang, and Guangxi perform well in terms of ecological environment quality, whereas Beijing, Tianjin, and Hebei perform relatively poorly. These disparities reflect differences in resource allocation and policy implementation for environmental governance across regions. Some regions, such as Fujian, Jiangxi, Zhejiang, and Hainan, have shown significant improvements, indicating effective measures and policies in environmental protection. However, regions like Beijing, Tianjin, Hebei, and Shanxi still have low environmental quality and need to strengthen their environmental governance and protection measures further.

To promote nationwide improvement in ecological environment quality, it is essential to increase environmental protection investment [61] and policy support [62] for underdeveloped regions, encourage green and sustainable development [63, 64], and strengthen interregional cooperation and experience sharing to improve overall ecological environment quality [65, 66]. In conclusion, while there have been certain improvements in China's ecological environment quality over the past decade, significant regional disparities remain. Through targeted policies and measures, it is possible to further enhance the ecological environment quality across the nation and promote sustainable development.

Analysis of Decoupling Relationships

An analysis of the decoupling relationship between the digital economy development level and ecological environment quality in China from 2011 to 2021 reveals significant regional differences. The decoupling index is used to measure the relationship between digital economy growth and ecological environment quality, where a negative value indicates that digital economy growth is accompanied by improvements in ecological environment quality, and a positive value indicates that digital economy growth is accompanied by deterioration in ecological environment quality (Table 3).

Beijing's decoupling index is 0.8864, indicating a situation of "recession coupling," where both the digital economy and ecological environment quality are declining. In contrast, Tianjin (-0.1875) and Hebei (-0.1116) have negative decoupling indices, indicating strong decoupling, where digital economy growth is accompanied by improvements in ecological environment quality. Other provinces and cities, such as Shanghai (-0.5874), Jiangsu (-0.4881), Zhejiang (-0.0671), and Anhui (-0.6275), also exhibit strong decoupling characteristics, indicating that these regions have found a balance between digital economy development and ecological environment protection.

On the other hand, regions such as Shanxi (0.0311), Inner Mongolia (0.6170), Liaoning (0.6754), Jilin (0.6887), and Heilongjiang (0.5503) have positive decoupling indices, indicating that digital economy development in these regions is accompanied by deterioration in ecological environment quality, classified as weak negative decoupling. Fujian (0.0930), Guangdong (0.7098), and Qinghai (0.1361) also fall into the weak negative decoupling category, where ecological environment quality has not significantly improved amid digital economy growth.

Nationally, the average decoupling index is -0.1037, indicating that overall, China has achieved strong decoupling, with digital economy development accompanied by improvements in ecological environment quality. However, there are significant regional differences, with some areas like Beijing and Liaoning still facing considerable environmental pressure.

Overall, the relationship between digital economy development and ecological environment quality varies significantly across provinces and cities. Beijing shows a decline in both the digital economy and ecological environment quality, while other regions like Tianjin, Hebei, and Shanghai have achieved strong decoupling, indicating improvements in ecological environment quality alongside digital economy growth. Jiangsu, Zhejiang, and Anhui have found a balance between digital economy development and ecological environment protection, achieving strong decoupling. The successful experiences of these regions can serve as references for other provinces. However, regions like Shanxi, Inner Mongolia, and Liaoning, where digital economy development is accompanied by environmental degradation, need to strengthen environmental protection measures to achieve sustainable development.

To promote nationwide improvement in ecological environment quality, it is essential to increase policy support and investment in regions with poor environmental quality, encourage green development, and promote sustainable development. Additionally, fostering interregional cooperation and experience sharing can help enhance the overall ecological environment quality across the country.

Specifically, Beijing, which shows a decline in both digital economy development and ecological environment quality (recession coupling), needs a comprehensive evaluation of environmental policies and economic development strategies to achieve a win-win situation. Tianjin and Hebei, which have significantly improved ecological environment quality alongside rapid digital economy growth, should continue to consolidate their achievements and promote green economic development. Shanghai, Jiangsu, Zhejiang, and Anhui, although facing certain environmental pressures amid digital economy development, have achieved strong decoupling through effective environmental protection measures. The successful practices in industrial structure adjustment and technological innovation in these regions can provide valuable lessons for other regions [67, 68].

Analysis of Coupling Coordination Degree

An analysis of the coupling coordination degree between the digital economy development level and ecological environment quality across Chinese provinces and cities from 2011 to 2021 reveals significant regional differences. The coordination degree measures the extent of coupling between digital economy development and ecological environment quality, with higher values indicating better coordination.

Beijing maintained a relatively high coordination degree from 2011 to 2020, growing from 0.2820 to 0.2816, but experienced a significant drop to 0.2036 in 2021, indicating some imbalance between digital economy development and ecological environment protection in certain years. Tianjin and Hebei saw their coordination degrees decrease from 0.1521 and 0.1199 in 2011 to 0.0860 and 0.0872 in 2021, respectively, showing insufficient efforts in ecological environment protection amid digital economy growth. Shanxi's coordination degree fell from 0.1199 in 2011 to 0.0779 in 2021, highlighting pronounced conflicts between digital economy development and ecological environment protection.

Inner Mongolia, Liaoning, Jilin, and Heilongjiang experienced slight fluctuations but generally maintained low coordination degrees of 0.1076, 0.1037, 0.0911, and 0.1019, respectively, indicating insufficient ecological environment protection efforts. Eastern coastal provinces and cities like Shanghai, Jiangsu, Zhejiang, and Anhui had relatively higher coordination degrees. Shanghai's coordination degree rose from 0.2062 in 2011 to 0.2152 in 2020 but declined to 0.1275 in 2021, indicating some conflicts between digital economy development and ecological environment protection in certain years. Jiangsu and Zhejiang had coordination degrees of 0.1170 and 0.1842 in 2021, showing a better balance between digital economy development and ecological environment protection. Anhui's coordination degree improved to 0.1016 in 2021.

Table 3. Decoupling Relationships between the Digital Economy Development Level and Ecological Environment Quality in China.

Area	ΔN	ΔE	$X_{N,E}$	Type
Beijing	-0.1160	-0.1308	0.8864	Recession Coupling
Tianjin	0.0358	-0.1910	-0.1875	Strong Decoupling
Hebei	0.0219	-0.1958	-0.1116	Strong Decoupling
Shanxi	-0.0056	-0.1802	0.0311	Weak Negative Decoupling
Neinenggu	-0.1062	-0.1722	0.6170	Weak Negative Decoupling
Liaoning	-0.1224	-0.1812	0.6754	Weak Negative Decoupling
Jilin	-0.1132	-0.1644	0.6887	Weak Negative Decoupling
Heilongjiang	-0.0658	-0.1196	0.5503	Weak Negative Decoupling
Shanghai	0.1109	-0.1888	-0.5874	Strong Decoupling
Jiangsu	0.0875	-0.1794	-0.4881	Strong Decoupling
Zhejiang	0.0134	-0.1993	-0.0671	Strong Decoupling
Anhui	0.1101	-0.1755	-0.6275	Strong Decoupling
Fujian	-0.0192	-0.2068	0.0930	Weak Negative Decoupling
Jiangxi	0.0872	-0.1981	-0.4402	Strong Decoupling
Shandong	0.0217	-0.2113	-0.1029	Strong Decoupling
Henan	0.1091	-0.1954	-0.5585	Strong Decoupling
Hubei	0.0432	-0.1497	-0.2888	Strong Decoupling
Hunan	0.0226	-0.1912	-0.1180	Strong Decoupling
Guangdong	-0.1500	-0.2114	0.7098	Weak Negative Decoupling
Guangxi	0.0270	-0.1840	-0.1465	Strong Decoupling
Hainan	0.0687	-0.2145	-0.3204	Strong Decoupling
Chongqing	0.0689	-0.1644	-0.4189	Strong Decoupling
Sichuan	0.0969	-0.1807	-0.5365	Strong Decoupling
Guizhou	0.0290	-0.1602	-0.1814	Strong Decoupling
Yunnan	0.0052	-0.1866	-0.0279	Strong Decoupling
Xizang	0.1034	-0.2475	-0.4177	Strong Decoupling
Shaanxi	0.0076	-0.1722	-0.0439	Strong Decoupling
Gansu	0.1218	-0.1242	-0.9808	Strong Decoupling
Qinghai	-0.0243	-0.1787	0.1361	Weak Negative Decoupling
Ningxia	0.0682	-0.2082	-0.3276	Strong Decoupling
Xinjiang	0.0430	-0.1345	-0.3196	Strong Decoupling
China	0.0187	-0.1806	-0.1037	Strong Decoupling

Fujian, Jiangxi, and Shandong showed varying degrees of fluctuation, with Fujian's coordination degree at 0.1669, Jiangxi's at 0.1109, and Shandong's at 0.0817 in 2021, reflecting mixed effectiveness in ecological environment protection amid digital economy growth. Central provinces like Henan, Hubei, Hunan, and Guangdong also experienced some fluctuation, with Henan's coordination degree at 0.0871, Hubei's at 0.1115, Hunan's at 0.0947, and Guangdong's at 0.1448 in 2021, indicating areas needing improvement in ecological environment protection.

Guangxi, Hainan, Chongqing, and Sichuan showed slight improvements over the observation period, with coordination degrees of 0.1088, 0.1495, 0.1227, and 0.1168 in 2021, respectively, indicating the gradual strengthening of ecological environment protection measures. Guizhou and Yunnan improved after 2017, with coordination degrees of 0.0755 and 0.0851 in

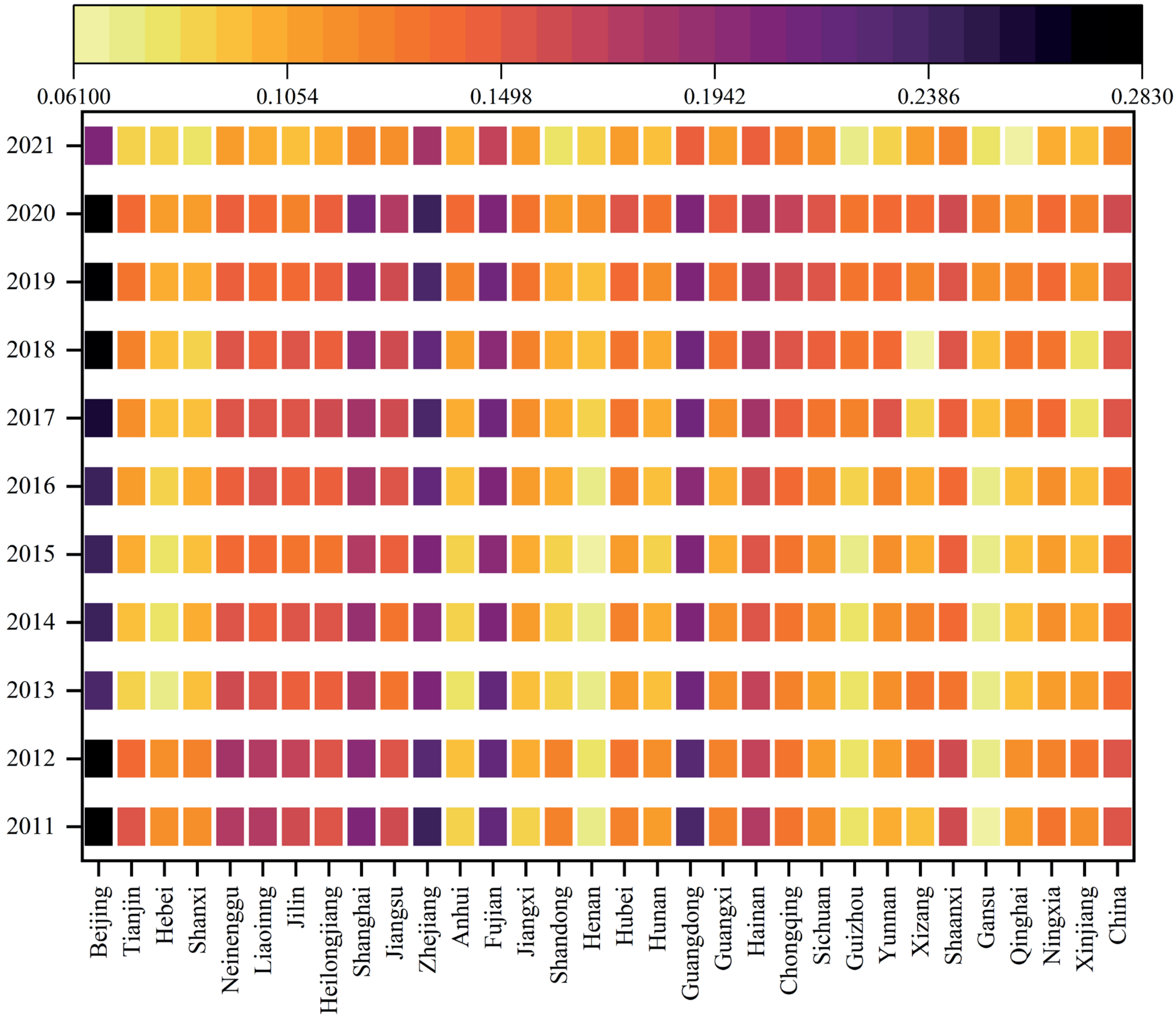

Fig. 3. Coordination Degree between the Digital Economy Development Level and Ecological Environment Quality in China (2011-2021).

2021, reflecting progress in balancing digital economy development and ecological environment protection.

Western provinces like Tibet, Shaanxi, and Gansu had relatively low coordination degrees, with Tibet at 0.1087, Shaanxi at 0.1246, and Gansu at 0.0832 in 2021, indicating substantial ecological environment pressure amid digital economy growth. Qinghai and Ningxia experienced some fluctuation, with Qinghai's coordination degree at 0.0659 and Ningxia's at 0.0992 in 2021, reflecting imbalances between digital economy development and ecological environment protection. Xinjiang's coordination degree decreased from 0.1128 in 2011 to 0.0957 in 2021, indicating insufficient efforts in ecological environment protection amid digital economy growth.

Nationally, the average coordination degree increased from 0.1552 in 2011 to 0.1614 in 2020 but dropped to 0.1209 in 2021, indicating overall fluctuations in the coordination between the digital economy and ecological environment quality, with a significant decline in 2021 possibly due to specific economic activities and environmental events. Overall, there are notable differences in the degree of coordination between digital economy development and ecological environment quality across provinces and cities.

Beijing and Shanghai had higher early coordination degrees but have seen declines in recent years, while eastern coastal provinces like Jiangsu and Zhejiang have found a better balance between digital economy development and ecological environment protection, indicating successful policy implementation and technological application. To enhance the practical value of policy recommendations, we propose more concrete and actionable strategies. For instance, establishing regional green technology innovation centers could drive localized advancements in sustainable practices. Additionally, creating targeted incentives for industries to adopt cleaner production methods can directly address specific environmental challenges. Moreover, developing cross-provincial collaborations to share best practices would facilitate the dissemination of successful strategies, enabling regions with lower coordination degrees to learn from those with higher performance. Central and western provinces like Henan, Gansu, and Qinghai have lower coordination degrees and need further environmental protection measures and policy support to achieve sustainable development goals. These regions face substantial ecological environment pressure amid digital economy growth and need increased investment in environmental protection and technological innovation to improve their coordination degrees.

To promote nationwide ecological environment improvement, it is essential to increase policy support and investment in regions with poor environmental quality, encourage green development, and promote sustainable development. Additionally, fostering interregional cooperation and experience sharing can help enhance the overall ecological environment quality across the country. Specifically, Beijing needs a comprehensive evaluation of environmental policies and economic development strategies to achieve a win-win situation. Tianjin and Hebei should continue consolidating their achievements and promoting green economic development. Shanghai, Jiangsu, Zhejiang, and Anhui should build on their successful experiences in industrial structure adjustment and technological innovation (Fig. 3).

In conclusion, there are significant differences in the relationship between digital economy development and ecological environment quality changes across China over the past decade. Targeted policies and measures can further enhance the ecological environment quality nationwide, promoting coordinated development between the digital economy and ecological environment. Strengthening policy support and investment in regions with poor environmental quality, fostering green development and sustainable development, and promoting interregional cooperation and experience sharing are crucial for ensuring that China achieves a win-win goal of rapid digital economy development alongside environmental protection and sustainable development.

Theil Index

The analysis of the Theil index for the coupling coordination degree between the digital economy development level and ecological environment quality in various regions of China from 2011 to 2021 shows significant differences between the eastern, central, and western regions. The Theil index measures inequality, with higher values indicating greater inequality (Fig. 4).

In the eastern region, the Theil index was 0.0151 in 2011, peaked at 0.0283 in 2020, and decreased to 0.0243 in 2021, indicating significant fluctuations in coordination during this period. This reflects that although the eastern region has rapidly developed economically [69], there are considerable disparities in the coordination of the digital economy and ecological environment quality among its provinces and cities. Some provinces might focus more on economic benefits while neglecting environmental protection, whereas others might have achieved a better balance.

In the central region, the Theil index was 0.0308 in 2011, gradually decreased to 0.0057 in 2020, and slightly increased to 0.0064 in 2021, indicating a reduction in inequality. This suggests that the central region has been enhancing ecological environment protection measures while promoting digital economy development, fostering more coordinated development among its provinces and cities. However, the slight increase in 2021 indicates that there is still room for improvement.

In the western region, the Theil index was 0.0344 in 2011, dropped to a low of 0.0065 in 2019, and rose to 0.0169 in 2021, indicating that inequality in coordination is decreasing but still fluctuating. Due to geographical and economic constraints, digital economy development in the western region has lagged, but recent policy support and infrastructure development have achieved some success in environmental protection.

Within regions, the Theil index was 0.0066 in 2011, reached a peak of 0.0113 in 2020, and was 0.0094 in 2021, showing that internal inequality is gradually increasing. This indicates growing disparities in coordination between digital economy development and ecological environment protection among provinces and cities, necessitating further internal coordination.

Between regions, the Theil index was 0.2039 in 2011, decreased to 0.1641 in 2012, gradually reduced to 0.1079 in 2020, and rose to 0.1435 in 2021, indicating overall improvement but still significant differences. The disparities between regions reflect gaps in economic development levels and environmental protection efforts, requiring policy guidance to promote coordinated regional development.

Overall, the Theil index was 0.2104 in 2011, reached its lowest value of 0.1192 in 2020, and was 0.1529 in 2021, indicating that nationwide inequality in coordination has fluctuated but shows a general trend of improvement. This suggests that while advancing digital economy development, China has also been strengthening ecological environment protection, achieving certain results.

The significant fluctuations in the Theil index in the eastern region indicate marked inequality in coordination between the digital economy and ecological environment quality. This may be due to the rapid economic development in the eastern region, but with differing policy implementation effects among its provinces and cities, leading to unbalanced coordination. The eastern region needs to further balance development among its provinces and cities, strengthen policy guidance and coordination, and improve overall coordination.

The gradual decline in the Theil index in the central region suggests reducing inequality in coordination

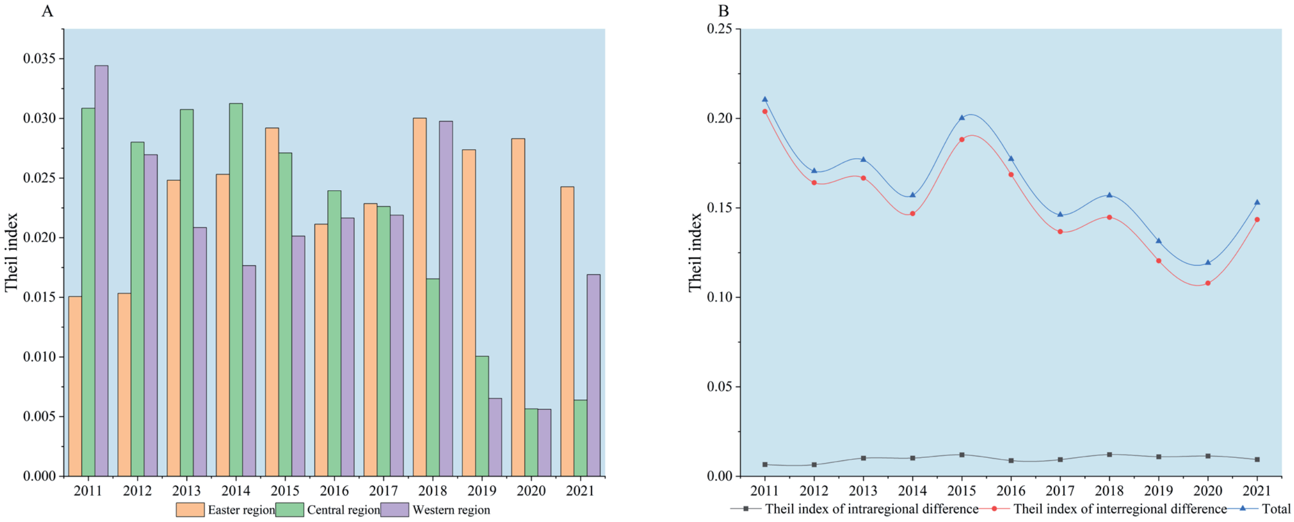

Fig. 4. The Theil Index of the Coordination Degree (2011-2021).

between the digital economy and ecological environment quality. The central region should continue to enhance regional coordinated development, further narrow internal disparities, and improve overall coordination through the introduction of advanced technology and management experiences.

Although the Theil index in the western region has fluctuated, the overall trend is decreasing, indicating improving coordination between the digital economy and ecological environment quality. The western region should continue to increase environmental protection investment, improve overall coordination, and promote regional coordinated development through policy support and infrastructure construction.

While internal inequality is gradually increasing, inter-regional inequality is generally improving but still significant. This indicates notable differences in coordination between the digital economy and ecological environment quality across different regions, necessitating further efforts to promote coordinated regional development and balanced nationwide development.

The nationwide Theil index shows that overall inequality in coordination between the digital economy and ecological environment quality is gradually improving, though it rose in 2021. Continued efforts are needed to promote coordinated development nationwide, ensuring the simultaneous advancement of the digital economy and ecological environment protection. Policy guidance and investment are crucial for promoting green development and sustainable development.

In conclusion, there are significant differences in the relationship between the development of the digital economy and changes in the quality of the ecological environment across China over the past decade. Targeted policies and measures can further enhance ecological environment quality nationwide, promoting coordinated development between the digital economy and the ecological environment. Strengthening policy support and investment in regions with poor environmental quality, promoting green and sustainable development, and fostering inter-regional cooperation and experience sharing are crucial for ensuring that China achieves a win-win goal of rapid digital economy development alongside environmental protection and sustainable development [70, 71].

Conclusions

This study analyzed the coupling coordination degree and Theil index of digital economy development levels and ecological environment quality across various regions of China from 2011 to 2021. The results show significant differences in coordination degrees between the digital economy and ecological environment quality across different regions. The eastern region has a higher level of digital economy development but exhibits substantial internal disparities. The central region shows gradual improvement in coordination, while the western region, despite making progress, still requires further enhancement.

Some provinces and cities, such as Beijing and Tianjin, face significant challenges, whereas regions like Jiangsu and Zhejiang have achieved a better balance. Certain provinces, like Tianjin and Hebei, have achieved strong decoupling between digital economy development and ecological environment quality, indicating that ecological environment quality improved alongside economic growth. In contrast, other provinces, such as Shanxi and Inner Mongolia, exhibit weak negative decoupling, suggesting that ecological environment quality did not improve in tandem with economic growth.

Nationally, the coupling coordination degree shows an overall improving trend, but there was a slight reversal in 2021, indicating the need for continued attention to regional coordinated development. To promote balanced development nationwide, it is essential to increase policy support and investment in the central and western regions, encourage green development, and improve overall ecological environment quality. Additionally, the eastern region should further optimize policies to promote internal regional coordination. Through interregional cooperation and experience sharing, coordinated development of the digital economy and ecological environment can be achieved, advancing the national sustainable development goals.

The results of this study provide a reference for formulating regional policies for digital economy development and ecological environment protection, highlighting the importance of targeted and inclusive policies to achieve more balanced and sustainable national development.

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Conflict of Interest

The authors declare no conflict of interest.

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