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Original Research

Coupling Coordinated Analysis of Digital Village Construction, Economic Growth and Environmental Protection in Rural China

Yuanqi Xie[1,2], Hui Liu[1]*

[1] Economic College, Hunan Agricultural University, Changsha, China;
[2] Accounting College, Hunan University of Finance and Economics, Changsha, China

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Abstract

Coordinating the development of the economy and environment has always been a tough challenge. The digital village construction in China offers unprecedented historical opportunities for rural areas to propel coordinated development and catch up with their urban counterparts. This paper used a coupling coordination degree model, exploratory spatial data analysis, and an obstacle degree model to investigate the coupling coordination of digital village construction, economic growth, and the environmental protection system (DEES) in rural China from 2015 to 2021. The results indicate: (1) The coupling coordination degree of DEES increases annually, yet a significant spatial imbalance among regions persists. (2) There is a positive spatial correlation in the coupling coordination of DEES, with the clustering trend gradually strengthening and subsequently weakening. (3) The most consistent obstacles are economic growth and per capita income, while obstacle factors vary among provinces. The results suggest that governments should increase investment in rural digital infrastructure, promote the synergistic efforts of the digital economy and green development, and drive the digitization of rural areas. Meanwhile, each province should use its own resources effectively, to make up for any shortcomings, thereby promoting coupling coordinated development in rural areas.

Keywords: DEES, coupling coordination degree, kernel density estimation, spatial autocorrelation, obstacle factors

Introduction

Following reform and opening-up, China has completed the transition from a planned economy to a market economy. However, a distinct dualistic structure has emerged in urban-rural areas, characterized by an incomplete market in rural areas and an overall lag in rural development compared to urban areas [1]. After the 1998 Asian financial crisis, China's economy experienced the onset of deflation [2]. Confronted with widespread overcapacity and a sluggish market, the adoption of an assertive fiscal policy became imperative [3]. To effectively stimulate economic recovery with constrained fiscal expenditures, it is crucial to strategically allocate funds to areas with rapid and tangible effects. Rural infrastructure investment stands out as the most beneficial realm for such fiscal allocation [4]. Since 1998, nationwide efforts in the reconstruction of rural

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* e-mail: liuh1220@163.com

power grids, road construction, river management, and extensive agricultural water conservancy projects have ensured a consistently high average annual growth rate of GDP [5-8].

However, in comparison to the needs for economic growth, both infrastructure and the environment continue to be significant constraints affecting rural economic development [9]. Pronounced economic and social disparities persist between China's urban and rural areas [10]. The income gap between urban and rural residents continues to widen, with the absolute difference in per capita disposable income increasing from 3,263 yuan in 1998 to 28,481 yuan in 2021 [11]. At the same time, China's environmental protection efforts have primarily targeted industrial and urban areas, resulting in relatively insufficient resources and funding for preventing agricultural and rural pollution [12, 13]. This has led to severe ecological damage in rural areas, marked by pollution from pesticides and fertilizers, solid waste, livestock and poultry feces, and vegetation destruction [14]. Hence, policymakers need to persistently focus on rural coordinated development, enabling more people to enjoy the benefits of economic growth.

As information technology continues to advance, various sectors are undergoing a wave of informatization and digitization [15-17]. The interaction between information technology and economic growth, environmental protection, and everyday life is progressively deepening, offering new historical opportunities for rural coordinated development. Since the early 21st century, there has been a systematic promotion of informatization in rural areas [18]. The "2006-2020 National Informatization Development Strategy" emphasized the importance of increasing rural internet accessibility at affordable rates [19]. In 2015, the central government initiated the nationwide promotion of "E-commerce in Rural Areas," aiming to facilitate the transformation of rural development and propel agricultural modernization [20]. In 2019, the central government issued the "Outline of the Digital Village Development Strategy," officially designating digital village construction as a strategic direction for rural revitalization [21]. With the rapid progress of nationwide digital village construction, it effectively promotes comprehensive development in rural areas [22].

In the current scenario, China's economy is experiencing a slowdown amidst complex global political and economic challenges, coupled with overheated real estate and industrial investments [23]. In response to these challenges, China has refocused its attention on rural areas, actively promoting rural revitalization to stimulate the development of the domestic economic cycle [24]. Policymakers aspire to achieve this objective through the implementation of digital village construction, emphasizing the integration and digitization of agriculture, ecology, and residential living. Digital village construction, as a driving force for China's rural economic growth and environmental protection, holds the potential to facilitate the coordinated development of the rural economy and environment [25]. Therefore, addressing the simultaneous enhancement of digital village construction, promoting rural economic growth, and advancing environmental protection in rural areas has emerged as an urgent research concern. Examining the coupling coordination level of digital village construction, economic growth, and the environmental protection system (DEES) is essential for promoting a positive development model in rural areas and achieving sustainable economic and environmental development.

Literature Review

Over the long term, scholars have consistently focused on the relationship between economic growth and environmental protection. One of the seminal studies related to the Environmental Kuznets Curve employed various indicators to explore the relationship between environmental quality and income. It suggests that environmental impacts tend to rise as economies become wealthier, reaching a peak before subsequently declining [26]. Scholars argue that the coordinated development of the economy and the environment does not equate to "equal development." The level of economic development determines the quality of the ecological environment, while the activities in the environment influence the economic development itself [27]. Thus, economic development and environmental protection should be seen as mutually reinforcing and synergistic. However, as a significant force within the digital economy, the impact of digital infrastructure on the coordinated development of both the economy and the environment remains an area that has not been comprehensively investigated and explored.

In the past few years, the economic effects of digital infrastructure have received much attention from scholars. Toader et al. have found that digital infrastructure, such as broadband, significantly contributes to economic growth [28]. Pradhan et al. outline the correlation between digital infrastructure and economic growth, empirically demonstrating that the convergence of financial and digital infrastructure creates new opportunities to bridge wealth gaps in developing countries [29]. Du et al., based on provincial panel data in China, have confirmed the substantial promoting effect of digital infrastructure [30]. This is achieved by promoting technological innovation, improving industrial structure, and enhancing production efficiency, taking into account regional heterogeneity. Tang and Zhao, using panel data from China from 2006 to 2017, have arrived at similar conclusions [31]. As the digital economy continues to advance, some scholars have explored the positive role of digitization in improving the environment. They argue that digital technologies possess characteristics such as high penetration, rapidity, and sustainability [32]. These features contribute to freeing traditional industries from excessive dependence on natural resources, breaking the segmentation of industrial chains, and providing possibilities for promoting green economic development [33, 34]. Di Silvestre et al. have discovered that the support of digital technology can facilitate technological progress in the energy sector, thereby accelerating the decarbonization process in different countries [35]. Wang et al., focusing on OECD countries, explore the impact and mechanism of digital technology on carbon emission intensity [36]. Wu et al., using the "Broadband China" strategy as a quasi-natural experiment, have confirmed that digital infrastructure can significantly save energy and reduce pollutant emissions [37].

However, the existing literature generally focuses on the economic or environmental effects of digital infrastructure, with few studies integrating all three aspects into a unified research framework. The interaction among digital village construction, economic growth, and environmental protection constitutes an open and collaborative system where these three components synergistically support each other. The coupling coordinated mechanisms within the ternary system can be outlined as follows: (1) Coupling coordinated effect of digital village construction. Firstly, digital village construction provides more efficient measures of agricultural production, enhancing output and diversifying rural industries for improved economic sustainability [38, 39]. Secondly, through intelligent agricultural management and precision agriculture, digital village construction reduces pollution risks to soil and water resources [40, 41]. It also establishes an environmental monitoring system to track the impact of agricultural activities on the surrounding ecosystem, enabling prompt preventive measures [42]. (2) Coupling coordinated effect of economic growth. Firstly, with rural economic growth, the government can invest more resources in digital village construction, such as rural communication stations and e-commerce platforms. It also attracts technology companies and investors to rural markets, continually driving digital village construction [43]. Secondly, rural economic growth facilitates the adoption of advanced environmental protection technologies and sustainable agricultural practices [44]. Additionally, it provides the government with more financial support, enabling higher environmental regulation requirements, enhancing environmental protection efforts, and achieving green development [45]. (3) Coupling coordinated effect of environmental protection. Firstly, a healthy ecological environment is the foundation for sustainable rural development [46]. Environmental protection serves as a driving force for the green development of digital village construction, enhancing the ecological environment. Secondly, environmental protection measures contribute to improving agricultural production conditions and increasing agricultural product yield and quality [47]. Additionally, these measures support the development of ecotourism by creating diversified economic income sources for residents, and promoting the sustainable development of rural economies [48].

In summary, digital village construction serves as an important force for the coordinated development of rural areas within the digital economy framework [49]. While

Table 1. The index system of the ternary system

Target system	Primary index	Secondary indicators	Unit	Effect	Weight
Digital village construction	Digital infrastructure	Rural internet broadband access rate (I1)	%	+	0.178
		Mobile phone ownership per 100 households (I2)	department	+	0.198
	Financial infrastructure	Coverage of digital financial inclusion (I3)	index	+	0.187
		Depth of use of digital financial inclusion (I4)	index	+	0.110
	Service platform	Rural delivery route length (I5)	km	+	0.147
		Number of Taobao Villages (I6)	unit	+	0.180
Economic growth	Economic structure	Value-added of the primary industry (i7)	yuan	+	0.103
		Share of the primary industry in GDP (I8)	%	+	0.125
		Share of employment in the primary industry (I9)	%	-	0.109
	Economic benefits	Per capita disposable income of rural residents (I10)	yuan	+	0.217
		Engel coefficient (I11)	%	-	0.106
		Grain yield per hectare (I12)	ton	+	0.091
	Economic inputs	Effective irrigation rate of arable land (I13)	%	+	0.093
		Mechanical power per hectare (I14)	kWh	+	0.072
		Fertilizer application per hectare (I15)	ton	+	0.084
Environmental protection	Resource utilization	Fiscal expenditure on environmental protection (i16)	yuan	+	0.208
		Per capita water resource availability (I17)	ton	+	0.184
	Ecological conservation	Forest coverage rate (I18)	%	+	0.178
		Area of soil and water conservation (I19)	km^2	+	0.163
	Environmental pressure	Amount of pesticide application (I20)	ton	-	0.120
		Usage of agricultural plastic films (I21)	ton	-	0.147

previous research extensively explores the coupling coordinated development of economy and environment, there remains a gap in understanding how digital village construction interacts with rural economy growth and environment protection, contributing to the coupling coordinated development of DEES. We constructed a comprehensive evaluation index system to accurately measure the coupling coordination degree of DEES across 30 provinces in China. Diverse methodologies, including the coupling coordination model, exploratory spatial data analysis, and the obstacle degree model, were applied to examine the coupling coordination level of DEES. Additionally, we introduced the kernel density estimation method to explore the dynamic evolution characteristics of the coupling coordination degree of DEES.

Material and Methods

Index System

According to existing research and following the principles of index system construction, we rely on the accessibility of indicator data to extract a subset of representative indicators [50, 51]. As seen in Table 1, we set up a multi-index system to analyze the coupling coordination level of three subsystems: digital village construction, economic growth, and environmental protection. To reflect the overall situation of China's rural areas, we plan to build the index system using nine dimensions: digital infrastructure construction, financial infrastructure construction, service platform construction, economic structure, economic benefits, economic inputs, resource utilization, ecological conservation, and environmental pressure [52-55]. Among them, share of employment in the primary industry (I9), Engel coefficient (I11), amount of pesticide application (I20), and usage of agricultural plastic films (I21) are negative indexes, while all other indexes are positive indexes.

Data Source and Processing

In 2015, the "E-commerce in Rural Areas" initiative marked the comprehensive implementation of the rural digitization transformation. Thereby, the sample in this study includes data from 30 provinces in China for the period 2015–2021. Due to data availability constraints, the sample excludes the regions of Tibet, Hong Kong, Macau, and Taiwan. The original data are from the China Statistical Yearbook, China Rural Statistical Yearbook, China Environmental Statistical Yearbook, China Urban-Rural Construction Statistical Yearbook, China Population & Employment Statistical Yearbook, and provincial statistical yearbooks for the respective years. For missing data, we use linear interpolation to fill the gaps.

Due to the diverse units of the indicators within the index system, direct comparability for analysis and modeling is impractical [56]. To maintain consistency in our research and mitigate any impact arising from differences in indicator dimensions and magnitudes, it is necessary to standardize the raw data before assessing coupling coordination degree [57]. We have adopted the extreme-value method to transform the indicators to be dimensionless [58]. For positive indicators (Zhang et al., 2011):

$$x'_{ij} = \frac{x_{ij} - \min x_j}{\max x_j - \min x_j} \tag{1}$$

while, for a negative index:

$$x'_{ij} = \frac{\max x_j - x_{ij}}{\max x_j - \min x_j} \tag{2}$$

where x'_{ij} represents the value of indicator j in year i, and $\max x_j$ and $\min x_j$ indicate the maximum and minimum value of indicator.

Comprehensive Evaluation Functions

Considering the varying degrees of significance that different indicators may carry within DEES, we use the entropy weight method to calculate indicator weights [59]. The specific steps are as follows:

First, the proportion of the indicator j in year i:

$$p_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{m} x'_{ij}} \tag{3}$$

Second, the information entropy of the indicator j:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} p_{ij} \ln p_{ij} \quad (0 \le e_j \le 1) \tag{4}$$

Third, the entropy redundancy for indicator j:

$$d_j = 1 - e_j \tag{5}$$

Fourth, the weight of indicator j:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{6}$$

Finally, we calculate the comprehensive evaluation of each subsystem in year j:

$$V_i = \sum_{j=1}^{n} V_{ij} = w_j \times x'_{ij} \tag{7}$$

where m is the number of years, and n is the number of indicators.

Coupling Coordination Model

Coupling Coordination Degree

The coupling coordination model includes the calculation of three important index values: the coupling degree, the comprehensive coordination index, and the coupling coordination degree [60]. Generally, the coupling coordination degree measures the strength of the association between two or more subsystems and is expressed by the following formulas when dealing with the ternary system:

$$C = \sqrt[3]{\frac{V_1 \times V_2 \times V_3}{\left[\frac{V_1 + V_2 + V_3}{3}\right]^3}} \tag{8}$$

$$T = \alpha V_1 + \beta V_2 + \gamma V_3 \tag{9}$$

$$D = \sqrt{C \times T} \tag{10}$$

where C represents the degree of coupling, V_1, V_2, and V_3 denotes the comprehensive evaluation index of digital village construction, economic growth, and environmental protection subsystems. T represents the comprehensive coordination index, reflecting the overall level of digital village construction, economic growth, and environmental protection. α, β and Y represent the contribution of the three subsystems, respectively. They satisfy $\alpha + \beta + \gamma = 1$. In this paper, we consider each subsystem equally important, so we make $\alpha = \beta = \gamma = 1/3$. D represents the coupling coordination degree.

To intuitively describe the coupling coordination level of DEES, we have established ranking criteria for the coupling coordination degree based on existing research [61, 62]. These criteria are given in Table 2.

Table 2. Criteria for evaluation of coupling coordination degree

Development stage	Coupling coordination degree	Coupling coordination level
Unbalanced development	0≤D≤0.2	Severe disorder
	0.2<D≤0.3	Substantial disorder
	0.3<D≤0.4	Moderate disorder
Transitional development	0.4<D≤0.5	Slight disorder
	0.5<D≤0.6	Primary coordination
Balanced development	0.6<D≤0.7	Moderate coordination
	0.7<D≤0.8	Good coordination
	0.8<D≤1	Excellent coordination

Kernel Density Estimation

In statistics, the kernel density estimation method is a non-parametric approach to estimating the probability density function of random variables [63]. This method allows the examination of temporal variations in estimated samples by constructing a density function based on their distribution characteristics. In this study, we adopt the Gaussian kernel function to describe the dynamics of DEES [64]. The specific formula for the density function is as follows:

$$p(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x_i - \bar{x}}{h}\right) \tag{11}$$

$$K(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \tag{12}$$

where x is random variables, x_i represents the comprehensive levels of subsystems for each province, $\bar{x}$ represents the average value of the comprehensive levels; n is the number of observations, and h is the bandwidth, which determines the precision in kernel density estimation.

Exploratory Spatial Data Analysis

Exploratory spatial data analysis comprises a set of analytical methods and techniques for visualizing spatial data to varying degrees, focusing on assessing the correlation between different regions in space, revealing the spatial distribution of data and its spatial clustering [65]. This is achieved by directly manipulating different perspectives of the data through dynamic connectivity statistics graphs [66]. It allows for both global and local spatial autocorrelation analyses. Therefore, we have adopted this method to analyze the spatiotemporal effects of the coupling coordination in DEES.

Spatial autocorrelation analysis often uses Moran's I to conduct the analysis [67]. The Global Moran's I can describe the degree of coupling coordination within a province and its correlation with neighboring provinces. The formula is defined as follows:

$$Global\ Moran's\ I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \bar{x})(x_j - \bar{x})}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \tag{13}$$

where n is the number of spatial units, $S^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n}$ is the sample variance; x_i and x_j represents values of coupling coordination of province i and j, $\bar{x}$ represents the average value of all provinces; W_{ij} is the spatial weight matrix, characterizing whether regions are adjacent, that is, for provinces i and j, if they are adjacent, then $W_{ij} = 1$; otherwise, $W_{ij} = 0$. The value of I indicates the global autocorrelation, which is between –1 to 1.

The Global Moran's I can determine whether there is spatial correlation in coupling coordination, but it cannot reveal which specific provinces exhibit spatial clustering [68]. To address this limitation, this paper introduces the Local Moran's I:

$$Local\ Moran's\ I_i = \frac{n(x_i - \bar{x})\sum_{j=1, j\neq i}^{n} W_{ij}(x_j - \bar{x})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{14}$$

where I_i is the Local Moran's index for province i; $(x_i - \bar{x})$ measures the disparity between the coupling coordination of province and the overall average level of all provinces, while $\sum_{j=1, j\neq i}^{n} W_{ij}(x_j - \bar{x})$ assesses the relative level of coupling coordination among neighboring provinces of province i compared to the average level. Using these two parts as the horizontal and vertical axes, the Moran scatterplot, composed of n provinces, can be divided into four quadrants corresponding to High-High, Low-Low, High-Low, and Low-High aggregation classifications.

Obstacle Degree Model

Identifying the obstacles that affect the coupling coordination of DEES is helpful in comprehending the underlying reasons for variations in coupling coordination degree across different regions [69]. In turn, this helps to provide more targeted recommendations to promote the coupling coordinated development of DEES. Therefore, we adopt the obstacle degree model to analyze the factors within the index system that impede the development of DEES, and the calculation formula is as follows:

$$I_{ij} = 1 - x'_{ij} \tag{15}$$

$$O_{ij} = \frac{w_j I_{ij}}{\sum_{j=1}^{n} w_j I_{ij}} \times 100\% \tag{16}$$

where x'_{ij} is the value of indicator j in year i, I_{ij} indicates the deviation degree of the indicator, w_j is the weight of indicator j obtained through the entropy method.

Results and Discussion

Comprehensive Evaluation Index Analysis

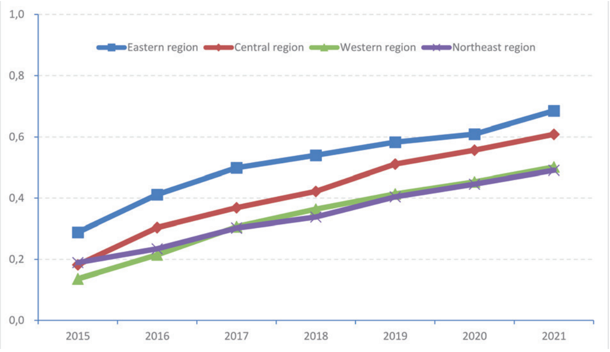
The comprehensive evaluation index for the subsystems of digital village construction, economic growth, and environmental protection is calculated using formulas (1)–(7). The results for specific years are presented in Table 3. From 2015 to 2021, the overall trend in China's rural digitization and economic and environmental development has exhibited a consistent year-on-year rise, characterized by stable growth. The mean level of digital village construction increased from 0.201 in 2015 to 0.583 in 2021, indicating a remarkable surge of 190.05%, with an annual average growth rate of 19.42%. Similarly, the average level of rural economic development increased from 0.334 in 2015 to 0.546 in 2021, reflecting a growth of 63.47%, with an annual average growth rate of 8.54%. Correspondingly, the average level of rural environmental protection increased from 0.287 in 2014 to 0.600 in 2022, denoting a growth of 109.06%, with an annual average growth rate of 13.08%. Across the nation, the pace of improvement in the construction of digital villages has already exceeded the growth rate in rural economies. This indicates the rapid development of digital villages as a crucial strategic focus for rural revitalization in recent years. In select eastern provinces like Jiangsu and Zhejiang, the comprehensive evaluation of all three subsystems consistently outperformed the national average. Meanwhile, certain western provinces, exemplified by the rapid development in digital village construction in Chongqing and Sichuan, have progressively diminished

Table 3. Comprehensive evaluation index of the three subsystems

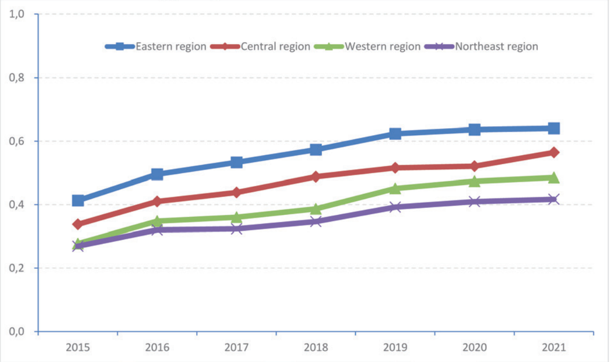
Region	Province	Digital village construction			Economic growth			Environmental protection		
		2015	2018	2021	2015	2018	2021	2015	2018	2021
Eastern region	Beijing	0.401	0.563	0.684	0.464	0.603	0.675	0.443	0.632	0.705
	Tianjin	0.235	0.502	0.610	0.320	0.442	0.484	0.293	0.522	0.630
	Hebei	0.153	0.395	0.539	0.361	0.455	0.461	0.209	0.406	0.480
	Shanghai	0.417	0.762	0.892	0.497	0.629	0.694	0.506	0.741	0.849
	Jiangsu	0.412	0.585	0.669	0.507	0.708	0.760	0.432	0.740	0.868
	Zhejiang	0.403	0.680	0.877	0.457	0.696	0.723	0.507	0.719	0.890
	Fujian	0.176	0.541	0.712	0.332	0.506	0.610	0.267	0.588	0.694
	Shandong	0.223	0.471	0.653	0.350	0.518	0.625	0.392	0.462	0.694
	Guangdong	0.187	0.466	0.663	0.487	0.693	0.809	0.386	0.609	0.789
	Hainan	0.278	0.433	0.553	0.355	0.481	0.563	0.302	0.547	0.684
Central region	Shanxi	0.178	0.368	0.543	0.340	0.436	0.483	0.175	0.361	0.429
	Anhui	0.191	0.430	0.564	0.344	0.476	0.529	0.269	0.451	0.651
	Jiangxi	0.153	0.412	0.632	0.345	0.471	0.589	0.239	0.457	0.635
	Henan	0.215	0.465	0.635	0.296	0.482	0.583	0.350	0.528	0.563
	Hubei	0.167	0.425	0.635	0.356	0.534	0.603	0.272	0.456	0.624
	Hunan	0.186	0.434	0.644	0.346	0.528	0.599	0.285	0.516	0.654
Western region	Neimenggu	0.078	0.235	0.343	0.252	0.319	0.356	0.156	0.262	0.338
	Guangxi	0.098	0.378	0.509	0.321	0.418	0.524	0.208	0.423	0.625
	Chongqing	0.175	0.485	0.623	0.422	0.529	0.670	0.296	0.505	0.648
	Sichuan	0.194	0.393	0.542	0.348	0.447	0.574	0.286	0.556	0.677
	Guizhou	0.162	0.385	0.468	0.236	0.350	0.450	0.214	0.439	0.484
	Yunnan	0.135	0.347	0.525	0.261	0.387	0.498	0.214	0.547	0.618
	Shaanxi	0.136	0.475	0.782	0.270	0.411	0.537	0.209	0.380	0.480
	Gansu	0.122	0.382	0.483	0.254	0.365	0.449	0.189	0.402	0.464
	Qinghai	0.090	0.263	0.333	0.223	0.330	0.365	0.179	0.327	0.416
	Ningxia	0.195	0.390	0.456	0.226	0.345	0.434	0.234	0.387	0.457
	Xinjiang	0.112	0.270	0.453	0.237	0.349	0.480	0.240	0.417	0.477
Northeast region	Liaoning	0.305	0.373	0.513	0.313	0.378	0.442	0.255	0.431	0.478
	Jilin	0.126	0.348	0.451	0.251	0.317	0.410	0.247	0.381	0.468
	Heilongjiang	0.136	0.293	0.509	0.244	0.345	0.399	0.347	0.450	0.539
Nationwide	Mean	0.201	0.432	0.583	0.334	0.465	0.546	0.287	0.488	0.600

the disparity with their eastern counterparts. Significantly, their comprehensive evaluation of each subsystem has surpassed even the national average, indicating a notable convergence in coupling coordinated development.

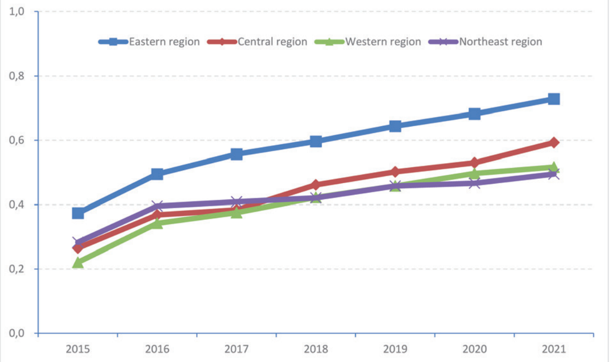
Empirical research has revealed significant developmental disparities between urban and rural areas in China, accompanied by discernible variations in economic levels across different regions [70, 71]. Figure 1 illustrates the temporal trend of the mean value of the comprehensive evaluation index in the three subsystems across the four regions of China from 2015 to 2021. As depicted in Figure 1(a), the rapid progress of digital village construction in China is evident, highlighting concurrent growth patterns in villages across diverse regions. The eastern region consistently leads each year, surpassing the other regions. Although the gap in digital village construction between the central and eastern regions is gradually narrowing, the western and northeastern regions still exhibit lower levels of rural digitalization. This emphasizes significant untapped potential for digital village construction, particularly in the less developed western and northeastern regions. Examining Figure 1 (b), we can see that rural economies across diverse regions in China have generally sustained a growth trend. Nevertheless, over the past three years, this momentum has notably decelerated, primarily due to the impact of international trade tensions and the pandemic. The eastern region has consistently sustained relatively robust economic growth, while rural areas in the northeast region have experienced subdued growth. Following years of development, the economic disparities among regions have progressively widened, displaying a step-like growth disparity between the eastern, central, and western regions. As depicted in Figure 1(c), a high level of urbanization in the eastern region has led to the near completion of the economic transition in rural areas, consistently maintaining a leading position in the effectiveness of environmental protection. The eastern region has strategically cultivated diverse rural landscapes characterized by green industries and ecologically sustainable living conditions, thereby enhancing the ecological resilience of rural areas. In contrast, other regions heavily rely on financial allocations to support green rural development, lacking effective internal mechanisms and driving forces for environmental protection. Nevertheless, the overall trend in the central and western regions indicates a gradual improvement.



(a) Comprehensive evaluation index of DVC



(b) Comprehensive evaluation index of EG



(c) Comprehensive evaluation index of EP

Fig. 1. Trends in the comprehensive evaluation index of the three subsystems in regions

Coupling Coordination Analysis

According to formulas (8)-(10), we can calculate the coupling coordination degree of DEES. Figure 2 depicts the kernel density curve for the period 2015–2021, illustrating the overall trends in the coupling coordination degree of DEES in rural China. Analyzing the distribution of the kernel density curve, it is evident that the distribution graph gradually shifts to the right, indicating an enhancement in the overall level of coupling coordination among digital village construction, economic growth, and environmental protection in rural China. However, during the early stages of the observation period, persistent side peaks and right tails on the side of the wave peak indicate a notable polarization phenomenon in the coupling coordinated development of DEES, with a substantial development disparity between provinces. Simultaneously, the peak height has shown a significant increase, suggesting a narrowing development gap between provinces. In the later stages of the observation period, although the height of the wave peak decreased, it remained higher than in the initial stage of the observation period. The disappearance of the side peak on the right side of the wave peak and the smoothing of the kernel density curve indicate a tendency towards the balanced development of coupling coordination between provinces, accompanied by a substantial reduction in the development disparity.

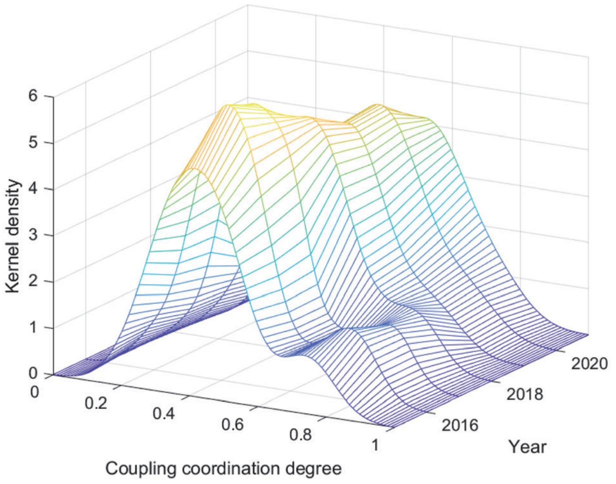
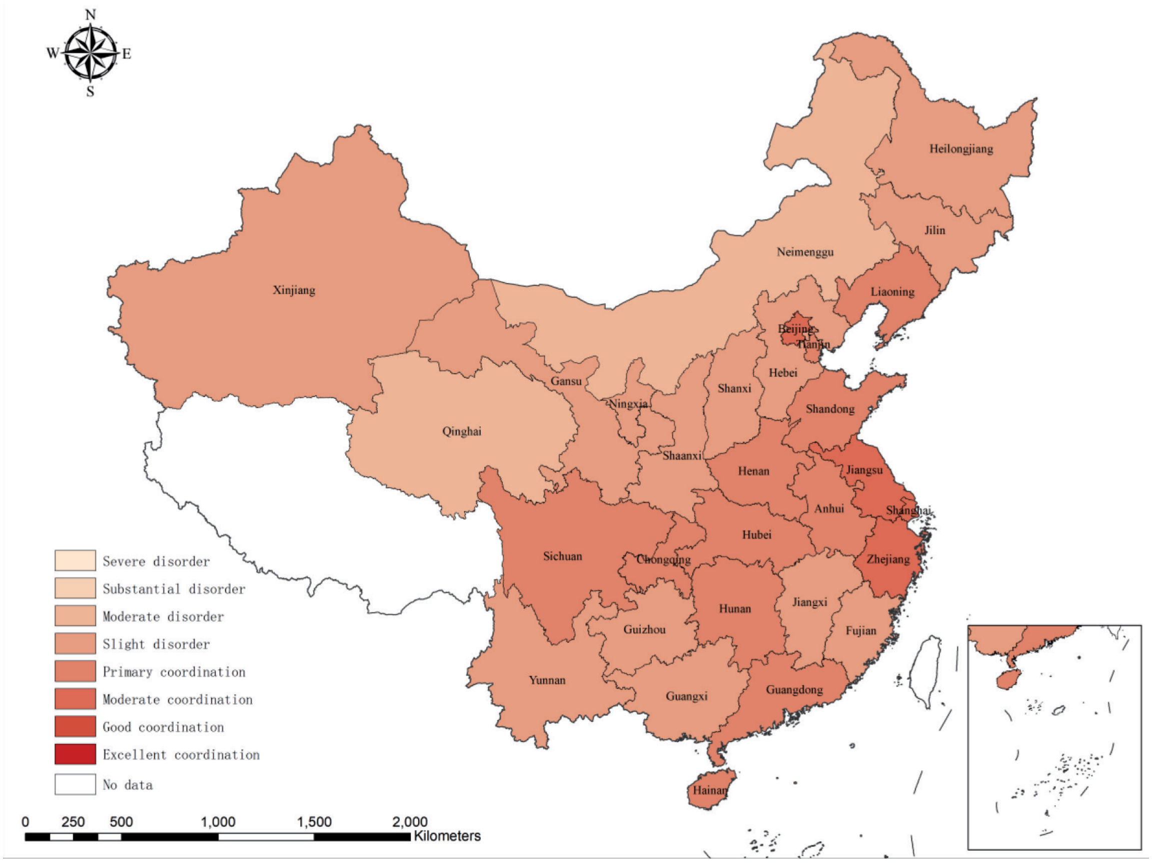


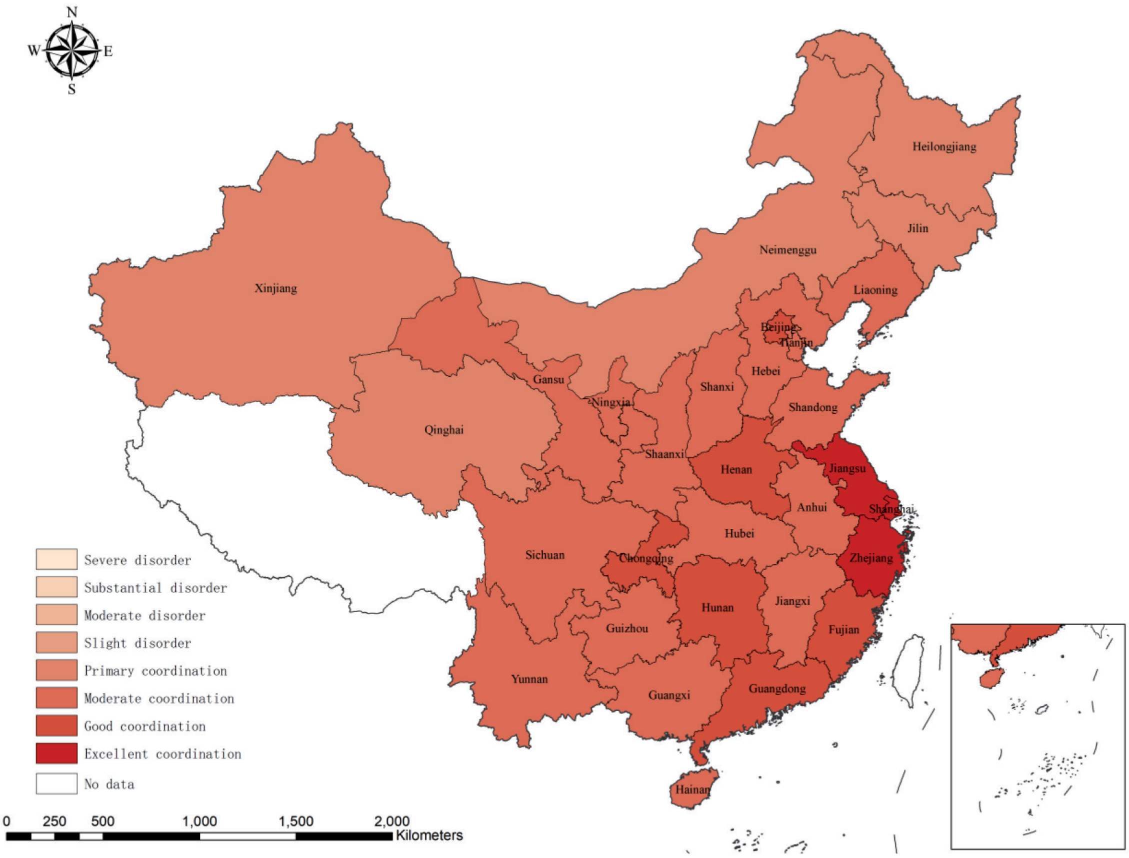
Fig. 2. Kernel density curve illustrating the coupling coordination degree of DEES

In summary, the trajectory of the kernel density curve throughout the observation period corresponds with the development process of China's digital village construction. The temporal changes in the coupling coordination degree of DEES highlight the positive impact of digital village construction in promoting the coupling coordinated development of rural economies and environments. Despite the significant improvement in the coupling coordinated degree of DEES during the observation period, the decline in the peak of the kernel density curve in the later period suggests that promoting the coupling coordinated development of rural China remains a long-term and challenging task.

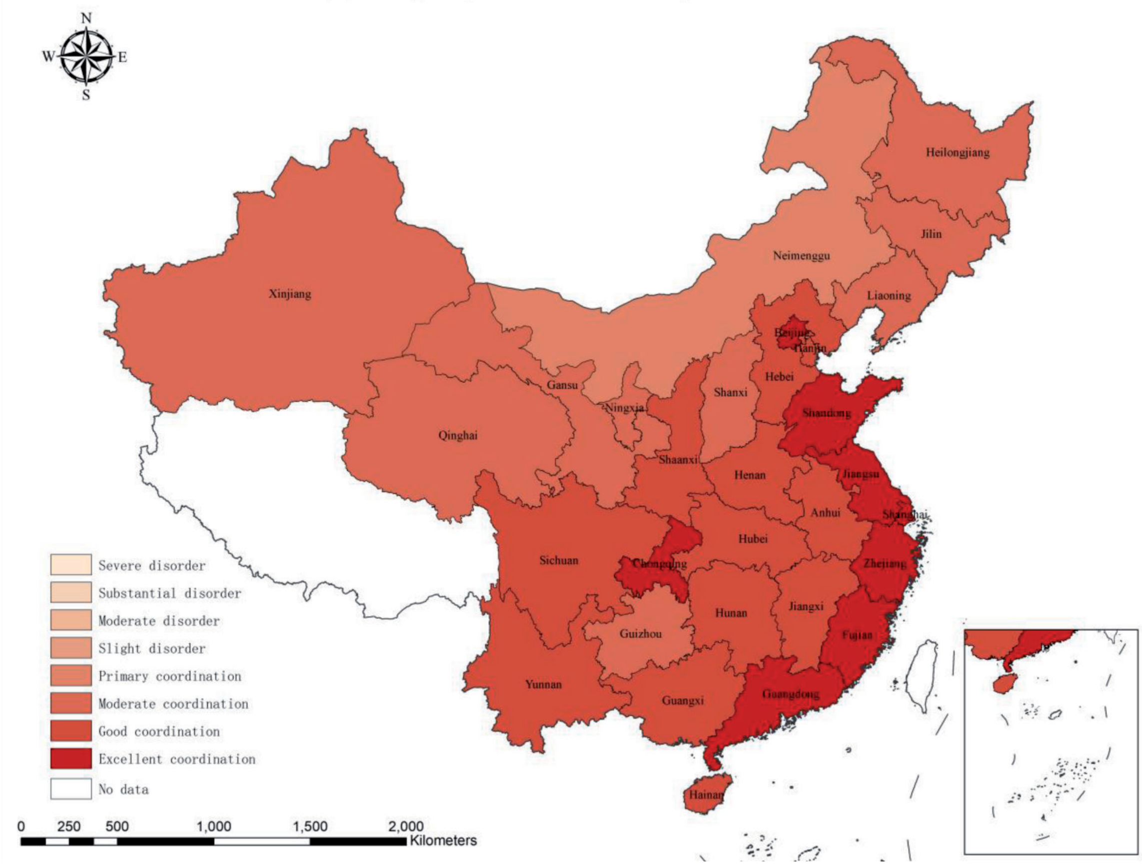
We generated a spatial distribution map of the coupling coordination degree for DEES. Figure 3 illustrates the dynamic evolution trend of the coupling coordination degree across provinces in China for the years 2015, 2018, and 2021. The observations reveal the following: (1) At the national level, there is a gradual increase in the coupling coordination degree each year, accompanied by noticeable shifts in the coupling coordination level. The progression from the transitional development stage to a balanced development stage is evident. (2) Analyzing the four major regions, we observe a transformation in their coupling coordination degrees from rapid growth to steady improvement. The eastern region led the transition to a balanced development stage in 2018, consolidating its leading position. The northeastern region exhibits the smallest increase in coupling coordination degree. The central and western regions, while generally hovering around the national average, experience more substantial increases. Furthermore, the disparity in coupling coordination level among the three major regions, excluding the east, is diminishing annually, with all regions currently at the level of primary coordination or higher. (3) At the provincial level, there is an observed increase in the coupling coordination degree, accompanied by variations in the level of coupling coordination among provinces. The eastern provinces, such as Shanghai, Jiangsu, and



(a) Coupling coordination degree in 2015



(b) Coupling coordination degree in 2018



(c) Coupling coordination degree in 2021

Fig. 3. Spatial distribution of coupling coordination degree of DEES

Zhejiang, are the first to achieve the excellent coordination level, while other provinces are in the process of catching up. In the western provinces, significant disparities exist. Chongqing has demonstrated the fastest development and has the highest level of coupling coordination, making it the only western province in the excellent coordination level. Neimenggu has progressed more slowly, with its coupling coordinated development still in the transitional development stage. Provinces in the central region show minimal disparities, with all except Shanxi in the level of good coordination. The northeastern provinces confront challenges such as massive population outflow, sluggish economic development, and considerable pressure on resources and the environment. Overcoming these obstacles is essential for their coupling coordinated development.

In conclusion, it is evident that the coupling coordination level of DEES has improved across all provinces. However, the fundamental dynamics of relative relationships persist, with a discernible trend of weakening from east to west remaining apparent. With the exception of a few provinces, relative differences between regions persist. Regarding the absolute value of the coupling coordination degree, the impact of digital village construction is particularly obvious in the eastern region, notably exemplified by Jiangsu and Zhejiang, highlighting significant aggregation effects. On the contrary, the coupling coordinated development of DEES in the western region presents significant opportunities for improvement, as the advantages of digital village construction have not yet fully manifested.

Spatial Correlation Analysis

Global Spatial Autocorrelation

In this study, we conducted a global spatial autocorrelation analysis of the coupling coordination degree across China's 30 provinces from 2015 to 2021. As presented in Table 4, the results reveal that the global spatial autocorrelation p-values for the coupling coordination degree of DEES in each year are all less than 0.01, with Z-scores exceeding 3.90. The results successfully passed the significance test, and the global Moran's I was consistently positive. This indicates a spatial clustering phenomenon in the coupling coordination level of DEES in rural China, suggesting a systematic spatial distribution where provinces with higher coupling coordination levels are adjacent to each other, as are provinces with lower coordination levels. The similarity among adjacent provinces is high, indicating a notable regional development imbalance.

Table 4. Global Moran's I of coupling coordination degree from 2015 to 2021

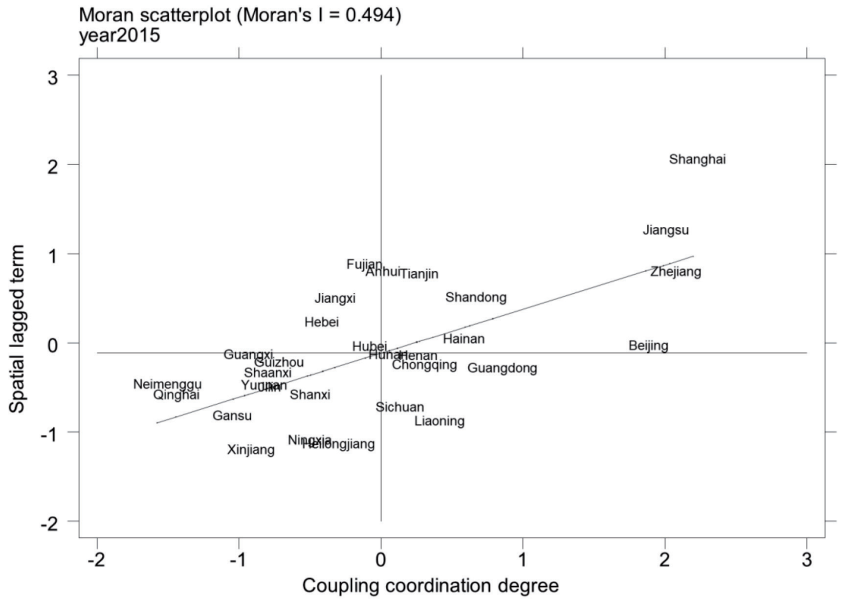
Variables	2015	2016	2017	2018	2019	2020	2021
Moran's I	0.405	0.421	0.423	0.512	0.525	0.509	0.427
z-score	3.960	4.104	4.144	4.913	5.015	4.873	4.147
p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Examining the overall trend from 2015 to 2019, the global Moran's I shows a consistent increase, suggesting that the coupling coordination level of DEES has been progressing to a state of clustering, with regional disparities widening. This aligns with the characteristics of rapid development in the early stages of digital village construction. Considering the results from 2019 to 2021, the global Moran's I exhibits a decreasing trend. Specifically, the global Moran's I value for 2021 is 0.427, significantly lower than the maximum value of 0.525 observed in 2019. It is also relatively close to the value in 2017. This suggests that, although there is a clustering phenomenon in the coupling coordinated development of DEES in rural China, the gap between provinces has not widened. Instead, there is a trend towards balanced development, reflecting the nationwide progress of digital village construction.

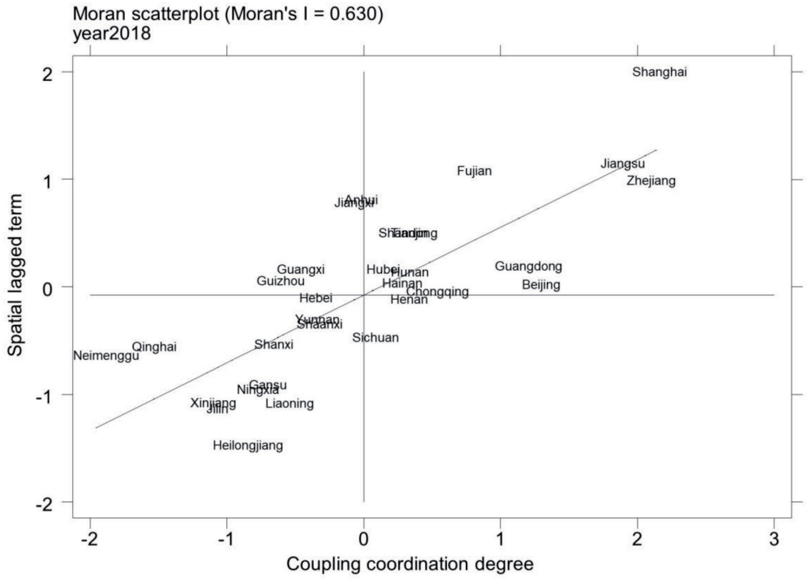
Local Spatial Autocorrelation

The global spatial autocorrelation analysis provides an overall perspective on the spatial correlation of the coupling coordination level in DEES across China's provinces. However, to assess the localized spatial clustering patterns of coupling coordination degree, particularly the spatial autocorrelation based on contiguity among provinces, we turn to the Moran scatter plots for further insights [68]. In this study, the Moran scatter plots illustrate the correlation between the coupling coordination degree of a specific province and the weighted average coupling coordination degree of its neighboring provinces. The horizontal axis represents the coupling coordination degree, while the vertical axis represents the spatial lagged term relative to the coupling coordination degree. Figure 4 illustrates the Moran scatter plots for the years 2015, 2018, and 2021.

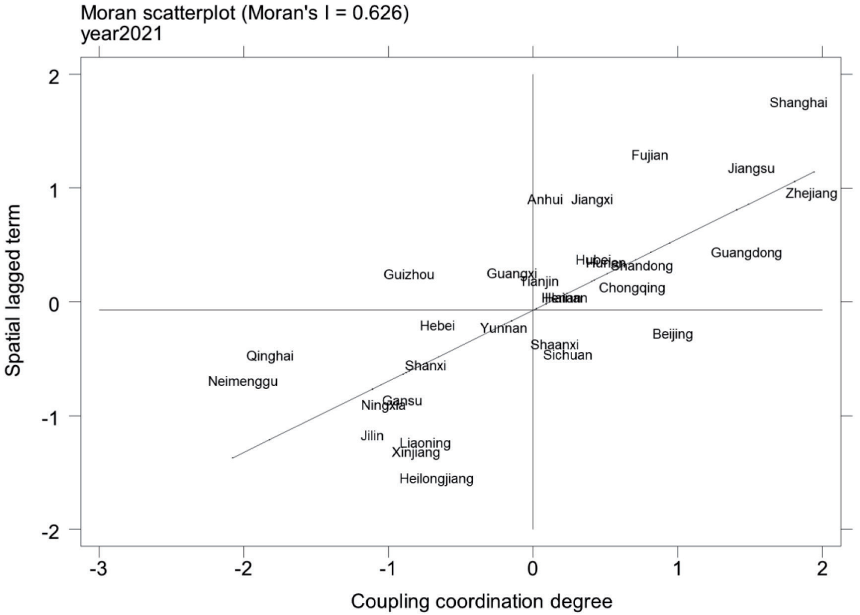
Combining the local Moran's I with Figure 4, the regional statistics detailing the significance of spatial autocorrelation for 30 provinces are presented in Table 5. Provinces located in the first and third quadrants indicate a positive impact from neighboring provinces on the coupling coordinated development. Conversely, those in the second and fourth quadrants suggest a negative impact from neighboring provinces. Examining Figure 4, points in the first and third quadrants increased from 21 in 2015 to 24 in 2021, indicating a strengthening positive impact on the regional coupling coordinated development of DEES. Meanwhile, points in the second and fourth quadrants decreased from 9 in 2015 to 6 in 2021, indicating a gradual reduction in the negative impact on the coupling coordinated development of DEES in those provinces. This suggests that specific provinces, such as Anhui and Beijing, may encounter challenges in integrating into the coupling coordinated development of neighboring regions or may have depleted considerable resources from adjacent areas, resulting in a significant negative impact. During the period from 2015 to 2021, the spatial spillover impact of DEES has surpassed competitive effects, thereby contributing to the coupling coordinated development among provinces.



(a) Moran scatter plot of 2015



(b) Moran scatter plot of 2018



(c) Moran scatter plot of 2021

Fig. 4. Moran scatter plot of coupling coordination degree

Table 5. Regional statistics of spatial autocorrelation significance for each province

Quadrants	2015	2018	2021
the first quadrant (HH)	Shanghai, Jiangsu, Tianjin, Zhejiang, Shandong, Hainan, Beijing	Shanghai, Jiangsu, Fujian, Zhejiang, Tianjin, Shandong, Guangdong, Hubei, Hunan, Hainan, Beijing, Chongqing	Shanghai, Fujian, Jiangsu, Zhejiang, Jiangxi, Guangdong, Hubei, Hunan, Shandong, Chongqing, Hainan, Henan
the second quadrant (LH)	Fujian, Anhui, Jiangxi, Hebei, Hubei	Anhui, Jiangxi, Guangxi, Guizhou	Anhui, Guangxi, Guizhou, Tianjin
the third quadrant (LL)	Hunan, Guangxi, Guizhou, Shaanxi, Neimenggu, Yunnan, Jilin, Qinghai, Shanxi, Sichuan, Gansu, Ningxia, Heilongjiang, Xinjiang	Hebei, Yunnan, Shaanxi, Sichuan, Shanxi, Qinghai, Neimenggu, Gansu, Ningxia, Xinjiang, Liaoning, Jilin, Heilongjiang	Hebei, Yunnan, Shaanxi, Qinghai, Shanxi, Neimenggu, Gansu, Ningxia, Jilin, Liaoning, Xinjiang, Heilongjiang
the fourth quadrant (HL)	Henan, Chongqing, Guangdong, Liaoning	Henan	Beijing, Sichuan

Obstacle Factors Identification

Obstacle Degree of Subsystems

The results of spatial correlation analysis indicate significant spatial variations in the coupling coordination degree during the research period. Therefore, it is imperative to further clarify the factors constraining the coupling coordination level of DEES across provinces. This precision is essential for devising targeted strategies to advance regional coordinated development. Using the obstacle degree model, we calculated the obstacle degrees for the three subsystems at the national level, as illustrated in Figure 5.

Evaluating the average obstacle degrees across all provinces from 2015 to 2021, the obstacle degrees of each subsystem, ranked from highest to lowest, are economic growth > digital village construction > environmental protection, with average obstacle degrees of 39.86%, 30.43%, and 29.71%, respectively. Further analysis reveals the following insights: Firstly, the impact of economic development consistently remains elevated throughout the research period, indicating that the economy is the most crucial factor constraining the improvement of the coupling coordination level of DEES. Secondly, the obstacle degree of digital village construction exhibits a fluctuating decreasing trend, indicating that robust national support and policy attention at the provincial level have resulted in positive outcomes for promoting digital village construction. Finally, the obstacle degree of environmental protection is increasing. After 2018, its obstacle degree surpasses that of digital village construction, becoming the second or even the primary obstacle factor. This highlights the importance of enhancing environmental protection as a crucial measure for promoting the coupling coordination level of DEES in rural China.

Obstacle Factors Analysis of Indicators

Depending solely on the obstacle degrees of subsystems to identify the obstacle factors to the coupling coordination level of DEES may inadvertently overlook individual differences in secondary indicators. Therefore, we further calculated the primary obstacle factors at the indicator level from 2015 to 2021 and ranked them based on obstacle degrees. Given the multitude of indicators,

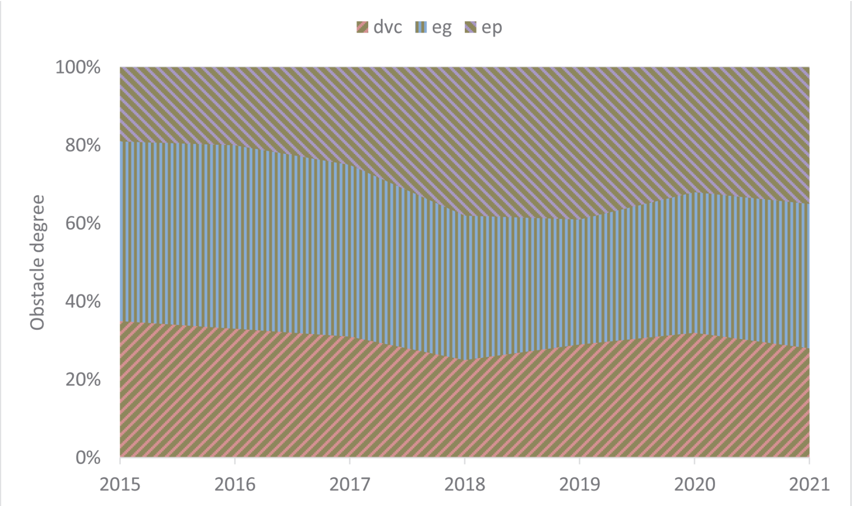


Fig. 5. Obstacle degree of the three subsystems from 2015 to 2021

we have listed the top 3 obstacle factors for each province in Table 6.

From a temporal perspective, the top three obstacle factors for each province remain relatively stable, primarily consisting of six indicators. Firstly, in the subsystem of digital village construction, obstacle factors include mobile phone ownership per 100 households (I2) and the number of Taobao Villages (I6). Mobile phone usage stands out as a significant constraint on the progress of digital village construction, providing robust support for production and daily life. Taobao Villages serve as indicators of the impact of digital village construction on the transformation of rural economic structures and the promotion of non-farm employment [53]. Secondly, in the subsystem of economic growth, the share of the primary industry in GDP (I8) and the per capita disposable income of rural residents (I10) are major obstacle factors. Per capita disposable income consistently holds the top position in obstacle degree levels almost every year, representing the most significant obstacle to the coupling coordinated development. The share of the primary industry in GDP reflects regional economic structures and the level of economic development. A lower share suggests mature development, with complex, diverse economic activities and a high level of coupling coordination. Thirdly, in the subsystem of environmental protection, fiscal expenditure on environmental protection (I16) and forest coverage rate (I18) are major obstacle factors. Fiscal expenditure on environmental protection exposes an imbalance between economic growth and environmental protection, indicating that economic development alone may not effectively improve the ecological environment. The forest coverage rate reflects the uneven distribution of natural resources across China, emphasizing significant disparities between supply and demand for environmental quality.

Table 6. The top three obstacle factors of indicators in provinces from 2015 to 2021

Province	2015			2016			2017			2018			2019			2020			2021		
Beijing	I10	I17	I18	I10	I18	I2	I18	I10	I2	I18	I10	I3	I18	I10	I17	I10	I18	I17	I10	I18	I17
Tianjin	I10	I18	I17	I10	I18	I16	I10	I18	I16	I10	I18	I17	I10	I18	I17	I10	I18	I16	I10	I18	I16
Hebei	I10	I17	I18	I10	I17	I18	I10	I17	I2	I10	I17	I2	I10	I17	I18	I10	I17	I18	I10	I17	I18
Shanghai	I10	I6	I8	I10	I17	I3	I10	I17	I6	I10	I3	I17	I17	I10	I18	I10	I17	I18	I10	I18	I17
Jiangsu	I10	I6	I1	I10	I5	I16	I10	I5	I16	I10	I5	I17	I10	I6	I17	I10	I6	I17	I10	I17	I18
Zhejiang	I10	I6	I1	I10	I6	I1	I10	I6	I3	I10	I6	I3	I10	I6	I17	I10	I17	I3	I10	I17	I3
Fujian	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I3	I10	I16	I3	I10	I16	I3	I10	I16	I3
Shandong	I10	I18	I6	I10	I18	I6	I10	I17	I6	I10	I17	I18	I10	I17	I6	I10	I18	I6	I10	I18	I6
Guangdong	I10	I6	I8	I10	I6	I5	I10	I6	I3	I10	I6	I3	I10	I6	I3	I10	I6	I3	I10	I6	I3
Hainan	I10	I16	I2	I10	I16	I6	I10	I16	I6	I10	I16	I6	I10	I16	I6	I10	I16	I6	I10	I16	I6
Shanxi	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I6
Anhui	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I6	I10	I16	I6	I10	I16	I2	I10	I16	I6
Jiangxi	I10	I16	I1	I10	I16	I1	I10	I16	I6	I10	I16	I6	I10	I16	I6	I10	I16	I6	I10	I16	I6
Henan	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I6	I10	I16	I6	I10	I16	I6
Hubei	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I6	I10	I16	I3	I10	I16	I6
Hunan	I10	I16	I1	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I6	I10	I16	I6	I10	I16	I6
Neimenggu	I10	I16	I1	I10	I18	I1	I10	I18	I5	I10	I18	I2	I10	I16	I5	I10	I18	I5	I10	I18	I2
Guangxi	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I6
Chongqing	I10	I8	I1	I10	I3	I2	I10	I8	I3	I10	I8	I3	I10	I2	I3	I10	I3	I2	I10	I3	I2
Sichuan	I10	I8	I1	I10	I8	I2	I10	I8	I5	I10	I8	I19	I10	I19	I5	I10	I19	I5	I10	I19	I5
Guizhou	I10	I8	I1	I10	I8	I1	I10	I8	I2	I10	I8	I2	I10	I8	I2	I10	I8	I2	I10	I8	I2
Yunnan	I10	I8	I1	I10	I8	I1	I10	I8	I2	I10	I8	I6	I10	I8	I5	I10	I8	I6	I10	I8	I6
Shaanxi	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I5
Gansu	I10	I16	I1	I10	I18	I1	I10	I18	I2	I10	I18	I2	I10	I18	I2	I10	I16	I2	I10	I16	I2
Qinghai	I10	I16	I2	I10	I16	I1	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I2	I10	I16	I2
Ningxia	I10	I16	I1	I10	I16	I2	I10	I16	I2	I10	I16	I6	I10	I16	I2	I10	I16	I6	I10	I16	I6
Xinjiang	I10	I16	I1	I10	I16	I5	I10	I17	I2	I10	I17	I16	I10	I16	I5	I10	I16	I5	I10	I16	I5
Liaoning	I10	I8	I1	I10	I8	I2	I10	I8	I2	I10	I8	I6	I10	I8	I6	I10	I8	I6	I10	I8	I6
Jilin	I10	I8	I1	I10	I8	I1	I10	I8	I1	I10	I8	I6	I10	I8	I6	I10	I8	I6	I10	I8	I2
Heilongjiang	I10	I8	I1	I10	I8	I1	I10	I8	I1	I10	I8	I2	I10	I8	I6	I10	I8	I6	I10	I8	I6

From a spatial perspective, each province presents distinct obstacle factors. Specifically, the economic growth in China is primarily led by the eastern provinces, which have exceptional advantages in digital infrastructure and economic development. The top obstacle factors are per capita disposable income of rural residents (I10), per capita water resource availability (I17), and forest coverage rate (I18). On one hand, the high population density leads to prominent contradictions between people and land, as well as significant income inequality. On the other hand, these provinces encounter natural disadvantages concerning forest coverage and water resources. Western provinces, such as Guizhou and Yunnan, may face challenges in digital village construction and economic growth. However, they possess unique resource advantages and demonstrate obvious characteristics of a "greening" economy. The major obstacle factors are the per capita disposable income of rural residents (I10) and the number of Taobao Villages (I6). Central provinces not only possess relatively scarce natural resources but also attract limited investment in technological innovation, making fiscal expenditure on environmental protection (I16) and the number of Taobao Villages (I6) the major obstacle factors. Northeast provinces have lagged in digital village construction, with a relatively high proportion of secondary industry in the economic structure, demanding a transformation in the mode of economic development and rational use of resources. Thus, each province should fully take advantage of exploring the path of coupled coordinated development of DEES, strengthening the strategic support role of the environment for green development, and using the "new engine" of the digital economy to promote the coordinated development of rural areas.

Conclusions

Based on the comprehensive evaluation index system, we adopted methods such as entropy analysis, coupling coordination degree model, exploratory spatial data analysis, and obstacle degree model to evaluate the coupling coordination degree of DEES in rural China from 2015 to 2021. The main findings are as follows: (1) The comprehensive evaluation index of rural digital village construction, economic growth, and environmental protection in China shows an overall increasing trend, with the spatial variation characterized by the pattern: East > Central > West > Northeast. The coupling coordination degree of DEES increases annually, progressing to a more coordinated and balanced state. However, there is spatial imbalance, forming a staircase decline from the east to the west. The western region, which initiated digital village construction later, exhibits a relatively low coupling coordination level, indicating significant development potential. (2) The global spatial autocorrelation analysis reveals a significant positive spatial correlation in the coupling coordination degree of DEES, with the clustering trend gradually strengthening from 2015 to 2019 and weakening thereafter. The local spatial autocorrelation analysis indicates distinct spatial correlation characteristics among neighboring provinces. Specifically, provinces with Low-High clustering and High-Low clustering include Anhui, Guangxi, Guizhou, Tianjin, Beijing, and Sichuan, while others are located in High-High clustering or Low-Low clustering. (3) Analysis based on the obstacle degree model indicates that obstacle factors of DEES in China exhibit both consistency and differences. The obstacle degree levels of each subsystem, from high to low, are economic growth, digital village construction, and environmental protection. Economic growth consistently maintains a high obstacle degree, while the obstacle degree for digital village construction shows a decreasing trend, and that for environmental protection exhibits an increasing trend. The main obstacle factors in each province include the per capita disposable income of rural residents, the number of Taobao Villages, and fiscal expenditure on environmental protection.

In view of the above conclusions, this paper provides the following suggestions: (1) Leverage the policy effects of digital village construction to create a new engine for rural economic development. Governments should increase investment in rural digital infrastructure, intensify efforts in talent development, accelerate the penetration of digital technologies into production and daily life, foster digital application scenarios, and create favorable conditions for the development of the rural digital economy. (2) Facilitating the integration of digital village construction and environmental protection to drive rural green development. Governments should take green transformation as a policy guide to lead rural green development, establish a green agricultural production system, enhance dynamic monitoring mechanisms for rural environments, and implement regulatory responsibilities for green development. (3) Relying on digital village construction, promote the synergistic efforts of the digital economy and green development. Empower green development with digital technology, lead the green transformation of rural production, distribution, and consumption, use digitization to enhance resource allocation efficiency, and drive the transformation and upgrading of rural economic structure. (4) In drawing up a differentiated strategy for regional coordinated development, each province should recognize the disparities it faces in terms of capital, technology, and natural resources. For prosperous provinces, efforts should be focused on strengthening environmental protection. In provinces abundant in natural resources, the emphasis should be on fully fostering new economic drivers and developing green industries. As for provinces with poor endowments, there is a need to balance economic and environmental coordinated development, enhancing the supportive role of digital technology in rural development.

However, there are still some limitations to this research. Firstly, we have focused on the coupling coordinated development of DEES in rural China, using data from mainland China as a sample. Therefore, the conclusions of this study need to take into account the local economic and environmental characteristics when replicated in other countries. Secondly, the lack of statistical data increases the difficulty of setting up a comprehensive index system. For example, the secondary indicators in digital village construction may be more representative when using the penetration of digital high-tech applications in listed companies, but the relevant data are not available. Thirdly, addressing rural coordinated development is a scientific problem worthy of comprehensive discussion in future research, which is lacking in this study. This can involve advocating for the development of a green economy and specific measures for effective energy conservation and emission reduction from a broader perspective [72, 73].

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Conflict of Interest

The authors declare no conflict of interest.

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