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Article

The coordinated development of higher vocational education, scientific and technological innovation, and sustainable economic development: Spatial distribution, influencing factors and future prediction

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Abstract: High-quality development in China requires higher vocational education, scientific and technological innovation, and sustainable economic development. The spatial distribution patterns of these factors show higher levels in the east and coastal areas compared to the west and inland regions, emphasizing the need for coupling coordination with the social economy. This study examines the impact of sustainable economic development on the coupling coordination degree using the spatial Durbin model. The results show a positive promotion and spillover effect, with regional variations. The main factors affecting the difference in coupling coordination are the amount of technology market contracts, fiscal expenditure on science and technology, patent application authorizations, tertiary industry output value, and the number of R&D institutions. According to the grey prediction model, the coupling coordination degree is expected to increase from 2022 to 2025, but achieving primary coordination may still be challenging in some areas. Therefore, strategies that utilize regional characteristics for coordinated development should be developed to improve the level of coupling coordination and create a mutually beneficial environment.

Keywords: higher vocational education; scientific and technological innovation; sustainable economic development; coupling coordination degree; spatial autocorrelation; grey model

1. Introduction

China's economy has transitioned from high-speed to high-quality development since 2012. This change has been accompanied by a series of policies and documents issued by the state to promote the development of higher vocational education (HVE). The "National Vocational Education Reform Implementation Plan" issued in 2020 underscores the importance of vocational education, placing it on par with higher education. This has propelled HVE onto a fast track of development.

The '14th Five-Year Plan' emphasizes the importance of innovation in the country's overall modernization efforts. Self-reliance and self-improvement in science and technology are strategic pillars for national development. It emphasizes facing the world's scientific and technological frontier and economic main battlefield. Universities play a crucial role in regional economic development as a strategic force in science and technology. They are responsible for serving scientific and technological innovation (STI) and act as the core driving force for promoting high-quality economic development in the region. The regional economy can effectively enhance the STI capabilities of universities through innovative development, achieving win-win results. This highlights the significance of a robust connection and coordination among HVE, STI, and sustainable economic development (SED).

This study examines the relationship between HVE, STI, and SED, which are key components of the 'rejuvenating the country through science and education' strategy. The research addresses a gap in the current literature by investigating the coupling coordination and spatial spillover of these three elements at a national level, a relatively underexplored topic. The study uses a comprehensive approach, employing the entropy method, coupling coordination model, and spatial autocorrelation analysis to measure and analyze the three systems. The findings aim to contribute to China's HVE, STI, and SED, and guide HVE to play a pivotal role in regional high-quality development.

The article is structured in the following manner. The second section comprises the literature review, while the third section encompasses the data sources, the construction of the evaluation system, and the introduction of research methods. The fourth section focuses on the analysis of the research results, and the fifth section includes the conclusions, discussions, innovations, shortcomings, suggestions, and prospects.

2. Literature review

At present, there are a certain number of studies on the coupling and coordination relationship between higher education and economic development, as well as the coupling and coordination relationship between higher education and STI. However, there are few papers on the relationship between HVE and the other two.

2.1. Coupling study of HE, STI, and SED

In the field of research on the coupled and coordinated relationship between HE and STI, numerous scholars have achieved notable research results. For instance, Yang and Cheng (2023) conducted a comprehensive investigation into the interdependent relationship between university science and technology innovation and sustainable economic development, further elucidating the intricate connection between the two. Guo et al. (2023) undertook an in-depth analysis of the interplay between urban resilience, low-carbon development, and higher education, emphasizing the pivotal role of these factors in fostering coordinated regional growth. By employing diverse research methodologies, Hu and Xu (2022) utilized patent data to examine the evolution of green agricultural technology in China, identifying spatial and technological development imbalances. Liu and Ma (2023) constructed a model of the coupling and degree of coordination between the low-carbon economy and regional sustainable development, and made optimistic predictions on the future degree of coupling and coordination between the two. These studies offer insights into the relationship between HE, STI, and SED, as well as valuable references for policy makers.

In addition, Wu and Chen's (2023) study revealed a high degree of coordination between regional economies and scientific achievements. Han et al. (2023) further explored the degree of coordination between digital economies, science and technology innovation, and ecology. Wang and Tang (2023) examined the coupled and coordinated relationship between innovation dynamics and innovation habitats from the perspective of spatial structure and network characteristics. Fu et al. (2023) observed the dynamic evolution of green technological progress and urban ecological resilience in terms of the degree of coupled coordination, while Wang et al. (2023) comprehensively assessed the degree of coupled coordination between regional STI and science and technology finance. It is noteworthy that Yang et al. (2023) conducted a comprehensive study on the spatio-temporal evolution characteristics of the coupled coordination of STI and economic development in the Guangdong-Hong Kong-Macao Greater Bay Area. Their findings indicate that the coupled coordination degree of urban quality and technological innovation within the region is on an upward trend. In addition, Zhang et al. (2023) elucidated the novel dynamics of digital economy and green technology innovation in the context of coupled and coordinated development. Wang and Su (2023) also conducted a comprehensive analysis of the spatial evolution of coordinated development between technological innovation in universities and regional economy, utilizing inter-provincial data in China. These comprehensive studies offer a multifaceted perspective on the interrelationships among HE, STI, and SED.

Scholars have conducted in-depth explorations on the relationship between HE and SED. Yang and Cheng (2023) revealed the mutual promotion relationship between higher education and economic development and its coupling logic. Xu et al. (2020) further elucidated the authors highlight the interdependence between higher education, economic growth, and innovation capacity, emphasizing their role in promoting coordinated regional development. Li and Liu (2021) employ a vector autoregression (VAR) model to analyze the dynamic relationship between higher education, technological innovation, and regional economic growth in depth and assess its coordination. Furthermore, Geng et al. (2023) constructed a coupled coordination mechanism between higher education and the digital economy and put forward relevant policy recommendations in their study. This provides a unique perspective for understanding the intrinsic connection between HE and SED.

Concurrently, numerous scholars have conducted comprehensive studies on the interrelationship between HE and SED in the Chinese context. An et al. (2024) and Han et al. (2023) employed a variety of analytical models to elucidate the actual situation of this relationship in China. In particular, Han et al. (2023) synthesized a variety of research methods to comprehensively assess the development of the demographic-economic and ecological-geological-environmental composite system in the Chengdu—Chongqing region. Geng et al. (2023), on the other hand, emphasized the importance of assessing the current state of development and the degree of coupled coordination in achieving sustainable development goals. From another perspective, Huang et al. (2023) conducted a comprehensive probabilistic analysis of the degree of coupling and coordination between graduate education and quality economic development. Geng and Tian (2023) focused on the measurement of coupled coordination between higher education and industrial structure. Additionally, Shi (2023) provided an in-depth discussion on the coupling mechanism between higher education and the digital economy. Collectively, these studies contribute to a more comprehensive understanding of the relationship between HE and SED.

In their examination of the nexus between HE, STI, and SED, scholars have conducted in-depth studies from various vantage points. Cheng et al. (2022) and Ma (2022) focus on the coupling relationship between higher education and economic development and the mutual influence are further explored by Huang et al. (2023) and Geng and Yan (2021). Furthermore, Ren and Zhou (2022) and Wang et al. (2021) conducted a comprehensive analysis of the dynamic relationship between higher education, technological innovation, and regional economic growth, as well as its coordination, using a vector autoregression (VAR) model and a coupled coordination model. Meanwhile, Li and Yi (2020) and Li et al. (2022) constructed a coupled coordination mechanism between higher education and the digital economy and proposed policy recommendations. Collectively, these studies demonstrate the pivotal role of HE in fostering socioeconomic advancement.

2.2. Coupling study of HVE, STI and SED

Although the academic community's understanding of the interrelationship between HE, STI and SED has been deepening, systematic research on the interactions between HVE, STI and SED is still insufficient. However, there are a number of scholars who have carried out exploratory studies.

At the provincial level, scholars have conducted in-depth discussions on the adaptation of HVE and regional economic development. These studies have covered a wide range of provinces, including Guangdong (Chen, 2020; Lin, 2022; Tao and Shan, 2019; Tao and Liao, 2016), Hainan (Liu and Chen, 2022), Zhejiang (Xu and Xu, 2022), Jiangsu (Jang and Zhang, 2023; You et al., 2021), and many other provinces. Additionally, studies have been conducted in Hainan (Liu and Chen, 2022), Zhejiang (Xu and Xu, 2022), Jiangsu (Jang and Zhang, 2023; You et al., 2021), and numerous other provinces. These studies have revealed the intricate and multifaceted interconnections between HVE and regional economies, providing a comprehensive empirical foundation for comprehending the interdependence between the two. In terms of coupling coordination degree research, scholars have analyzed the interactions among HVE, STI, and SED from different perspectives. Zhan et al. (2023) focused on the coupling relationship between the quality of secondary vocational education and the upgrading of the industrial structure, and pointed out that the mechanism of coordinated development between the two still needs to be further explored. Ren and Zhou (2022) explored the coupling coordination degree, emphasizing the importance of interdisciplinary and cross-field cooperation. Yu and Yu (2023) provided new insights into understanding the complex relationship between HVE, STI and SED from the perspective of the interaction between cultural industry and STI. Moreover, national studies offer valuable insights. Liu and Liu (2024) evaluated the integration of industry and education in vocational education, providing empirical evidence for optimizing the allocation of educational resources. Ye (2022) conducted a comprehensive analysis of the coupled and coordinated relationship between the scale of vocational education in the western region and the regional economy, demonstrating the intrinsic connection between the two.

Although studies have revealed some relationships between human vulnerability to environmental change HVE, STI, and SED, there are still many unanswered questions in this area. For example, what are the core features of each of HVE, STI, and SED? How do they interact with each other? Are there differences in spatial and spillover effects of these interactions across geographic regions? Solving these questions is important for a deeper understanding of the interactions among the three. Consequently, future research should concentrate on the spatial influence mechanisms and spillover effects between HVE, STI and SED in order to elucidate the intricate interconnections between them. By employing interdisciplinary and cross-field collaborative research, we can gain a more comprehensive understanding of the intrinsic laws of this interdisciplinary field and provide a more scientific basis for policy formulation and practice.

3. Materials and methods

3.1. Data source

The research objects for this study are the HVE, STI, and SED of 31 provinces, autonomous regions, and municipalities directly under the central government (excluding Hong Kong, Macao, and Taiwan). The data used in this study were obtained from the 'China Statistical Yearbook', 'China Education Statistical Yearbook', 'China Science and Technology Statistical Yearbook', 'China High-tech Industry Statistical Yearbook', and the EPS database, covering the period from 2012 to 2021. In cases where data was missing for individual years, linear interpolation was used for interpolation processing.

3.2. Indicator system

After a comprehensive review of academic studies on HVE (Pan and Weng, 2021; Sun et al., 2023), STI (Gao et al., 2023; Song and Li, 2019), and SED (Cai et al., 2022; Peng and Wu, 2021; Song and Li, 2019), we applied the principles of representativeness of indicator selection, ease of data access, and operability of evaluation to ensure the reliability and validity of our findings. In selecting indicators, we adhered to the principles of representativeness, data accessibility, and operationalizability. After comprehensive studies, we constructed a comprehensive evaluation index system for HVE, science and technology innovation, and regional socio-economic development. The system was constructed by following the core principles of representativeness in the selection of indexes, ease of access to data, and operability of evaluation. The system provides a comprehensive and systematic reflection of the core elements of the aforementioned three areas, as illustrated in **Table 1**.

The HVE system selects three first-level indicators and six second-level indicators for teaching scale, teaching quality, and teaching expenses. The STI system selects three first-level indicators and seven second-level indicators for the scale of scientific and technological, the expenditure on scientific and technological, and the income of scientific and technological. Finally, the SED system selects three first-level indicators and eight second-level indicators for economic scale, economic benefits, and economic structure.

Table 1. Comprehensive evaluation index system of HVE, STI, and SED.

System layer	First level indicators	Secondary indicators	Unit	Positive index/negative index	Weight	Reference source
HVE	Teaching scale	Number of students	Number	+	16.02%	(Pan and Weng, 2021; Sun et al., 2023)
		Number of schools	Number	+	10.40%	
	Teaching quality	Number of full-time teachers	Number	+	12.17%	
		The total investment of scientific research funds in higher vocational colleges	10,000 yuan	+	27.98%	
	Teaching expenses	State financial expenditure on education	1000 yuan	+	15.37%	
		The value of teaching instruments and equipment in higher vocational colleges	10,000 yuan	+	18.06%	
STI	The scale of scientific and technological	The full-time equivalent of R&D personnel	People per year	+	12.94%	(Gao et al., 2023; Song and Li, 2019; Wang and Su, 2023)
		Number of R&D institutions	Number	+	20.00%	
	The expenditure on scientific and technological	R&D expenditure	10,000 yuan	+	11.87%	
		Financial expenditure on science and technology	100 million yuan	+	10.69%	
	The income of scientific and technological	The number of authorized patents	Number	+	12.97%	
		The amount of the signed contract in the technology market	10,000 yuan	+	16.63%	
		The main business income of the high-tech industry	100 million yuan	+	14.91%	
SED	Economic scale	GDP	100 million yuan	+	7.92%	(Cai et al., 2022; Peng and Wu, 2021; Song and Li, 2019)
		per capita GDP	Yuan	+	5.74%	
		The level of residents' consumption	%	+	2.06%	
	Economic benefits	The fixed assets investment of the whole society	100 million yuan	+	38.18%	
		Total import and export trade volume	10,000 dollars	+	20.73%	
		Local fiscal revenue	100 million yuan	+	7.93%	
	Economic structure	The output value of the secondary industry	100 million yuan	+	8.51%	
		The output value of the tertiary industry	100 million yuan	+	8.91%	

3.3. Method

3.3.1. The entropy method

Entropy is a parameter used in thermodynamics to describe the state of matter. Its physical meaning is to represent the degree of disorder in the system. The entropy method uses information entropy to judge the degree of discreteness of data, thereby judging the effectiveness and value of evaluation indicators. The weight of the index increases with the degree of discreteness and entropy value. The study uses the entropy method to calculate the comprehensive development index of HVE, STI, and SED based on the degree of discreteness and entropy value. The calculation steps are as follows.

(1) Indicator normalization

In this study, let x_{ij} the original data of indicators, x'_{ij} be the standardized data after processing, then:

$$x'_{ij} = (x_{ij} - x_{j\min})/(x_{j\max} - x_{j\min}), x_{ij} \text{ the larger the better} \quad (1)$$

$$x'_{ij} = (x_{j\max} - x_{ij})/(x_{j\max} - x_{j\min}), x_{ij} \text{ the smaller the better} \quad (2)$$

where, $i = 1, 2, \dots, m$ (the number of evaluation years); $j = 1, 2, \dots, n$ (the number of evaluation indicators).

(2) Calculation of entropy values of evaluation indicators

Let E_j be the information entropy of the j-th indicator; let $K = 1/\ln m$ be a constant; $P_{ij} = x'_{ij}/\sum_{i=1}^{m} x'_{ij}$ be the proportion of the i-th year j-th indicator to that indicator, then:

$$E_j = -K\sum_{i=0}^{m}(P_{ij}\ln P_{ij}) \tag{3}$$

To avoid the situation of $\ln = 0$, when $P_{ij} = 0$, let $P_{ij} = 0.0000001$.

(3) Calculation of weights of evaluation indicators

Let θ_j be the entropy value (weight) of the j-th indicator, then:

$$\theta_j = \frac{1 - E_j}{\sum_{j=1}^{n}(1 - E_j)} \tag{4}$$

Among them, for the j-th indicator, the heavier the entropy weight, the greater the impact of the indicator on the system, and vice versa.

3.3.2. Coupling coordination model

Coupling refers to the interaction between two or more systems or forms of motion, resulting in mutual connection and influence. The degree of coupling measures the correlation between systems and represents their mutual dependency. In this context, there is an interactive coupling relationship between social security and economic and social development. When the systems cooperate and achieve mutual benefits, the coupling is benign; when the systems friction with each other and restrict each other, the coupling is adverse. Given the widespread applicability of coupling degree to different problems, this paper selects the coupling coordination model to measure the coupling coordination relationship between HVE, STI, and SED. The specific operation steps are as follows.

(1) Constructing the coupling coordination model

Let $X_1, X_2, \ldots, X_m$ be the m evaluation indicators of HVE, $Y_1, Y_2, \ldots, Y_n$ be the n evaluation indicators of STI, and $Z_1, Z_2, \ldots, Z_h$ be the h evaluation indicators of SED. Then, the comprehensive development values of the three indicators are:

$$U(X) = \sum_{i=1}^{m}\alpha_i X'_i \tag{5}$$

$$U(Y) = \sum_{i=1}^{n}\beta_i Y'_i \tag{6}$$

$$U(Z) = \sum_{i=1}^{h}\gamma_i Z'_i \tag{7}$$

$$0 \le U(X) \le 1, 0 \le U(Y) \le 1, 0 \le U(Z) \le 1 \tag{8}$$

Among them, $U(X), U(Y), U(Z)$ represent the comprehensive levels of HVE, STI, and socioeconomic development, respectively. $\alpha_i, \beta_i, \gamma_i$ are the weights of evaluation indicators of the three systems, respectively. X'_i, Y'_i, Z'_i are the standard values of the three systems. The formula for calculating the coupling coordination degree is:

$$C = \frac{\sqrt[3]{U(X) \times U(Y) \times U(Z)}}{U(X) + U(Y) + U(Z)} \tag{9}$$

Among them, C is the coupling degree, which satisfies $0 \leq C \leq 1$. When $C = 0$, it indicates that the three systems are unrelated and developing in opposite directions; when $C = 1$, the coupling degree is maximum, indicating that the systems are coupled benignly and tend to a new ordered structure. The larger C is, the more obvious the collaboration between systems is, and the stronger the coupling effect is.

(2) Model construction of coupling coordination degree

The coupling coordination degree only reflects the interaction among systems and does not include information at the development level. Therefore, the coupling coordination degree is introduced to comprehensively analyze the coordination degree of HVE, STI, and SED. The degree of coupling coordination can indicate the level of coordinated development, reflect the coupling status of HVE, STI, and SED, and further indicate the overall collaborative effect. It has stronger explanatory power compared to the coupling degree model. The calculation formula for coupling coordination degree is as follows:

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

$$W = a \times U(X) + b \times U(Y) + c \times U(Z) \tag{11}$$

Among them, D is the coupling coordination degree; W is the comprehensive evaluation index of the coupled system; a, b, c are the coefficients to be determined, and $a + b + c = 1$. According to existing research results, it is considered that the three are equally important, so $a = b = c = 1/3$.

The evaluation of the coupling coordination level involves dividing the coupling coordination degree into different intervals. To achieve this, the uniform distribution function method for coupling coordination degree discrimination and classification is adopted, as shown in **Table 2**, which is commonly used in academic segmentation.

Table 2. Coupling coordination degree classification standard.

Coupling coordination level	The interval of coupling coordination degree D value	Coordination level	The degree of coupling coordination
Low-level (Disorderly development)	(0.0~0.1)	1	Extremely imbalance
	[0.1~0.2)	2	Serious imbalance
	[0.2~0.3)	3	Moderate imbalance
Middle-level (Transitional development)	[0.3~0.4)	4	Mild disorder
	[0.4~0.5)	5	Borderline disorder
	[0.5~0.6)	6	Strenuously coordinated
	[0.6~0.7)	7	Primary coordination
High-level (Coordinated development)	[0.7~0.8)	8	Intermediate coordination
	[0.8~0.9)	9	Good coordination
	[0.9~1.0)	10	Coordination of high quality

3.3.3. Economic impact analysis

(1) Spatial weight matrix

The spatial econometric analysis is carried out using both the geographical adjacency matrix and the economic distance matrix. The geographical adjacency matrix reflects the neighboring status of regions, as shown in Equation (12), where "0" means not adjacent and "1" means adjacent. The economic distance matrix reflects the similarity of economic development among regions, as shown in Equation (13), where GDP is the per capita amount.

$$w_{ij} = \begin{cases} 0, i \text{ and } j \text{ are not adjacent} \\ 1, i \text{ and } j \text{ are adjacent} \end{cases} \tag{12}$$

$$w_{ij} = \begin{cases} 0, i = j \\ 1/\left|\text{GDP}_i - \text{GDP}_j\right|, i \neq j \end{cases} \tag{13}$$

(2) Spatial autocorrelation measure.

The global Moran's I index. The global Moran's I index tests whether the attribute values of neighboring areas in the whole region are similar, opposite, or independent of each other, and the value range is [−1, 1]. When it is close to −1, it is negatively correlated, when it is close to 1, it is positively correlated, and when it is close to 0, it is in the independent state without spatial correlation. The calculation method is as shown in Equation (14):

$$x = \frac{\sum_{i=1}^{n}\sum_{j\neq i}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{s^2 \sum_{i=1}^{n}\sum_{j\neq i}^{n} w_{ij}} \tag{14}$$

Among them, x_i and x_j are the observation values of regions i and j region respectively. $\bar{x}$ is the sample mean, s^2 is the variance, w_{ij} is the spatial weight matrix, and n is the sample size.

The local Moran's I index. The local Moran's I index of region i, I_i represents its correlation with the surrounding regions, with a value range of −1 to 1. When I_i is positive, similar elements are clustered together; when I_i is negative, dissimilar elements are clustered together. Based on the local Moran's I index, we can identify the clustering types of various provinces.

$$I_i = \frac{x_i - \bar{x}}{s^2}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x}) \tag{15}$$

(3) Spatial regression model

Due to the flow of talents, funds, technology and other factors among provinces, HVE, STI, and SED may generate spatial spillovers. To test the influencing factors of the coupling coordination degree of HVE, STI, and SED, the spatial Durbin model is selected for analysis. The model's basic structure is as follows:

$$Y = \alpha + \rho W + \beta X + \lambda W X + \theta \tag{16}$$

Among them, Y is the explained variable, X is the explanatory variable α, the constant term is, W is the spatial weight matrix, β is the regression coefficient, ρ is the coefficient of the spatial lag of the explained variable Y, λ is a parameter vector, and θ is the random disturbance term that follows the independent distribution. To reasonably interpret the coefficients of spatial regression models, Lesage (2008) proposed the partial differential method of spatial regression models. That is to decompose the impact of an explanatory variable on the dependent variable into direct effect and indirect effect, and their sum is the total effect.

Based on the basic expression of the spatial Durbin model and the selected impact variable indicators, this paper constructs a spatial Durbin model for the research of HVE, STI, and SED. Specifically, it is as follows:

$$\begin{aligned} D_{it} = {} & \alpha + \rho \text{WD}_{it} + \beta_1 \text{lnPGDP}_{\text{it}} + \beta_2 \text{RDP}_{it} + \beta_3 \text{RDI}_{it} + \beta_4 \text{HTEC}_{it} + \beta_5 \text{TRADE}_{it} + \beta_6 \text{STRUC}_{it} + \lambda_1 \text{lnPGDP}_{it} \\ & + \lambda_2 \text{RDP}_{it} + \lambda_3 \text{RDI}_{it} + \lambda_4 \text{HTEC}_{it} + \lambda_5 \text{TRADE}_{it} + \lambda_6 \text{STRUC}_{it} + \theta \end{aligned} \tag{17}$$

In Equation (17), the dependent variable *D* is the coupling coordination degree, the core explanatory variable PGDP is the per capita GDP, and the rest are control variables. RDP is the number of R&D personnel per 10,000 people, RDI is the proportion of R&D expenditure in GDP, HTEC is the proportion of high-tech industry income in GDP, TRADE is the proportion of import and export in GDP, and STRUC is the proportion of the output value of the tertiary industry in GDP.

3.3.4. Grey model

(1) Gray correlation analysis

Gray correlation analysis can reflect the relationship strength between dependent and explanatory variables in terms of correlation coefficients, which have the characteristics of high data utilization rate and high model accuracy. It can clearly explain the impact of explanatory variable changes on dependent variables. Gray correlation analysis generally includes the following steps: (1) selecting original data, determining the mother sequence and characteristic sequence; (2) dimensionless treatment of data; (3) calculating absolute value sequence; (4) calculating the maximum difference and minimum difference; (5) calculating gray correlation matrix; (6) calculating gray correlation degree and correlation sequence.

(2) Grey prediction GM(1,1)

The coupling coordination degree of HVE, STI, and SED in various regions from 2022 to 2025 is predicted by using the gray prediction model GM(1,1).

Firstly, define the original sequence.

$$X_0 = [X_0(1), X_0(2), \dots, X_0(m)], X_0(k) \geq 0, k = 1, 2, \dots, m\dots \quad (18)$$

Secondly, the original sequence is accumulated to the first order to obtain the accumulated generating sequence.

$$X_1 = [X_1(1), X_1(2), \dots, X_1(m)], X_1(k) = \sum_{i=1}^{k} X_0(i)\,, k = 1,2, \dots, m.. \quad (19)$$

Again, establish a first-order linear differential equation of X_1.

$$\frac{\mathrm{d}X_1}{\mathrm{d}t} + aX_1 = \mu \quad (20)$$

Finally, the first-order linear differential equation is solved by using the least squares method to obtain the prediction model.

$$x_1^P \hat{X}(k+1) = \left[X_n(1) - \frac{\mu}{a}\right] e^{-ak} + \frac{\mu}{a}, k = 1,2, \dots, m.. \quad (21)$$

Among them, μ is the gray action quantity, a is the gray development coefficient. If the test result satisfies both $P > 0.7$ and $C < 0.65$, the prediction result is relatively reliable.

4. Results

4.1. Comprehensive evaluation of HVE, STI, and SED

4.1.1. National situation

China's economy has experienced steady and rapid growth, with significant progress in economic and social development from 2012 to 2021. During this period, the scale of China's HVE and STI has also improved significantly, and the three are in a synchronized development state. **Figure 1** shows the coupling coordination results of HVE, STI, and SED in China from 2012 to 2021, according to the coupling coordination formula.

It can be seen from **Figure 1** that the HVE index $U(X)$, STI index $U(Y)$, and SED index $U(Z)$ have shown a growing trend. With 2014 as the dividing line, before 2014, the HVE index $U(X)$ and STI index $U(Y)$ lagged behind the SED index $U(X)$, and from 2014 onwards, the advanced HVE index $U(X)$ and STI index $U(Y)$ exceeded the SED index $U(Z)$. This fully demonstrates that China's HVE and STI have developed from lagging to a moderate level of anticipation.

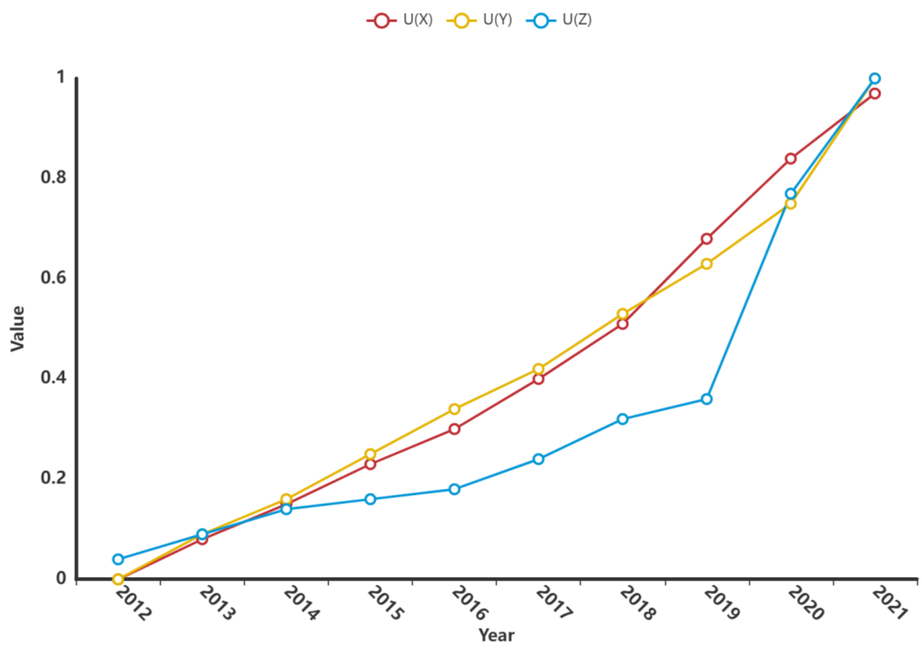


Figure 1. Comprehensive development of HVE, STI, and SED in China from 2012 to 2021.

4.1.2. Analysis of the situation in different regions

As shown in **Table 3**, the HVE index $U(X)$, STI index $U(Y)$, and SED index $U(Z)$ in different regions have shown an upward trend and synchronized development during the period of 2012–2021. In 2021, the HVE, STI, and SED in 12 provinces are synchronized. However, the difference between $U(X), U(Y)$, and $U(Z)$ cannot accurately reflect the coupling coordination among them, which requires the introduction of a coupling coordination model for analysis. Since there is almost no case that the difference is exactly equal, the provinces $|U(X) - U(Y) - U(Z)| < 0.05$ are judged as synchronized development types.

Table 3. Difference in levels of HVE, STI, and SED among regions: $U(X) - U(Y) - U(Z)$.

Province	Year = 2012				Year = 2021			
	$U(X)$	$U(Y)$	$U(Z)$	Difference	$U(X)$	$U(Y)$	$U(Z)$	Difference
Beijing	0.338	0.115	0.111	0.111	0.565	0.289	0.247	0.029
Tianjin	0.144	0.051	0.092	0.001	0.210	0.086	0.184	−0.060
Hebei	0.225	0.033	0.093	0.099	0.322	0.106	0.380	−0.163
Shanxi	0.149	0.017	0.052	0.080	0.180	0.044	0.137	−0.001

Table 3. (*Continued*).

Province	Year = 2012				Year = 2021			
	$U(X)$	$U(Y)$	$U(Z)$	Difference	$U(X)$	$U(Y)$	$U(Z)$	Difference
Inner Mongolia	0.100	0.014	0.072	0.013	0.137	0.019	0.153	−0.035
Liaoning	0.218	0.048	0.110	0.060	0.294	0.073	0.155	0.066
Jilin	0.117	0.014	0.052	0.050	0.167	0.020	0.131	0.016
Heilongjiang	0.173	0.022	0.057	0.095	0.238	0.027	0.124	0.087
Shanghai	0.186	0.097	0.160	−0.071	0.361	0.200	0.333	−0.171
Jiangsu	0.428	0.340	0.254	−0.166	0.656	0.638	0.845	−0.826
Zhejiang	0.244	0.168	0.164	−0.088	0.402	0.489	0.588	−0.676
Anhui	0.240	0.055	0.061	0.123	0.396	0.221	0.390	−0.215
Fujian	0.155	0.053	0.092	0.010	0.280	0.143	0.389	−0.252
Jiangxi	0.178	0.019	0.053	0.106	0.280	0.133	0.299	−0.151
Shandong	0.346	0.137	0.185	0.023	0.583	0.334	0.658	−0.409
Henan	0.299	0.056	0.093	0.150	0.546	0.173	0.520	−0.147
Hubei	0.291	0.048	0.078	0.165	0.426	0.205	0.386	−0.164
Hunan	0.260	0.041	0.069	0.150	0.404	0.154	0.408	−0.158
Guangdong	0.372	0.262	0.333	−0.223	0.787	0.914	0.891	−1.018
Guangxi	0.135	0.015	0.055	0.065	0.268	0.055	0.252	−0.039
Hainan	0.028	0.002	0.028	−0.003	0.051	0.008	0.058	−0.016
Chongqing	0.133	0.025	0.057	0.051	0.253	0.089	0.239	−0.076
Sichuan	0.271	0.044	0.082	0.144	0.458	0.159	0.419	−0.120
Guizhou	0.074	0.009	0.032	0.034	0.203	0.036	0.169	−0.001
Yunnan	0.113	0.011	0.042	0.061	0.210	0.033	0.238	−0.061
Tibet	0.000	0.000	0.020	−0.019	0.007	0.001	0.032	−0.027
Shaanxi	0.202	0.030	0.059	0.113	0.319	0.114	0.276	−0.070
Gansu	0.077	0.008	0.028	0.042	0.133	0.020	0.079	0.033
Qinghai	0.006	0.002	0.024	−0.020	0.025	0.004	0.049	−0.027
Ningxia	0.020	0.003	0.021	−0.004	0.039	0.011	0.050	−0.022
Xinjiang	0.063	0.006	0.047	0.010	0.132	0.012	0.138	−0.018

4.2. The coupling coordination analysis of HVE, STI, and SED

4.2.1. Coupling coordination analysis of the whole country

As shown in **Figure 2**, from 2012 to 2021, the coupling degree of HVE, STI, and SED in the whole country has always been kept at a high level, while the coupling coordination degree has shown a significant growth trend, gradually shifting from low-level extreme imbalance to high-level high-quality coordination.

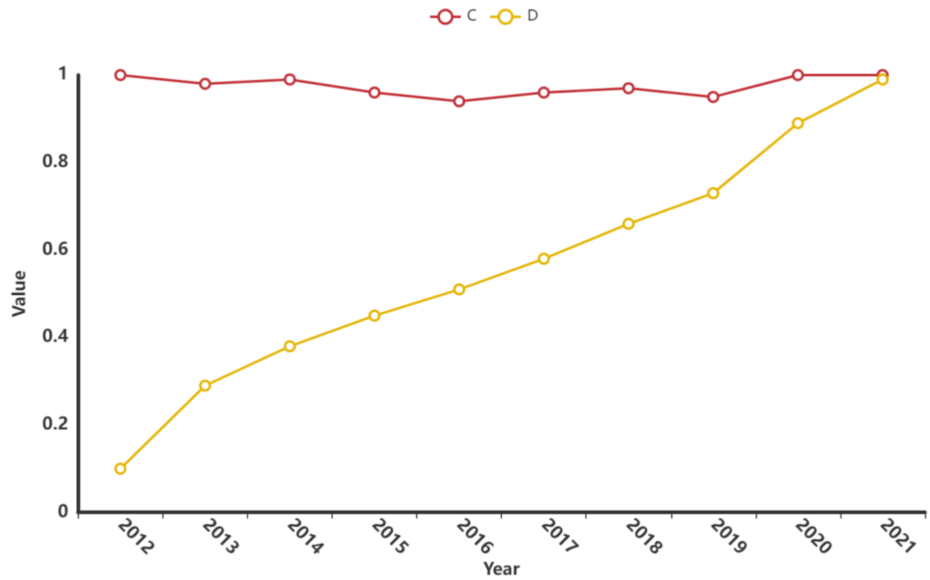


Figure 2. The coupling coordination degree of national HVE, STI, and social-economic development from 2012 to 2021.

4.2.2. The analysis of coupling coordination degree in various regions

Figures 3 and **4** illustrate the changes in coupling coordination in different regions from 2012 to 2021, based on the coupling coordination model. The benign coupling level among the three systems of HVE, STI, and SED in various regions is generally not high. Only Guangdong, Jiangsu, Shandong, Zhejiang, and other regions have been in the high-level coordination stage for a long time. Gansu, Guangxi, Guizhou, Hainan, Heilongjiang, Jilin, Liaoning, Inner Mongolia, Ningxia, Qinghai, Tianjin, Tibet, Xinjiang, Yunnan, Chongqing and other regions have always been in the middle and low level of disharmony stage. There are significant differences in coupling coordination among regions.

From 2012 to 2021, the coupling coordination degree of HVE, STI, and SED in various regions has shown different levels of leapfrogging, as shown in **Table 4**. In terms of the degree of change, the coupling coordination relationship grades in Tibet, Qinghai, Ningxia, and Xinjiang remain unchanged. Tibet, Qinghai, and Ningxia are in a state of severe imbalance, and Xinjiang is in a state of severe imbalance. Tianjin, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shanghai, Yunnan, and Gansu have changed their coupling coordination relationship by two grades. However, only Shanghai has reached a barely coordinated state. Beijing, Hebei, Jiangsu, Fujian, Shandong, Henan, Hunan, Guangxi, Hainan, Chongqing, and Guizhou have crossed three grades of coupling coordination relationships. However, only Beijing, Jiangsu, Shandong, and Henan have reached the level of primary coordination or above. Among them, Jiangsu and Shandong have reached a good coordination and intermediate coordination state. Zhejiang, Anhui, Jiangxi, Hubei, Guangdong, Sichuan, and Shaanxi have crossed four grades of coupling coordination relationships. Only Zhejiang, Anhui, Hubei, Guangdong, and Sichuan have reached the level of primary coordination or above. Among them, Zhejiang and Guangdong have reached high-quality coordination and good coordination states respectively. Jiangsu, Shandong, Zhejiang, and Guangdong, which are located on the eastern coast, have good education, science and technology, and economic levels and can rapidly improve in a short time. Tibet, Qinghai, Ningxia, Xinjiang, Hainan, and Gansu are located in the western region with weaker education, technology, and economic foundations. The coupling coordination relationship has been in a state of imbalance for a long time. There are significant regional differences in the coupling coordination relationship between HVE, STI, and SED. The differences in starting points of regional development levels make the differences in coupling coordination relationships more significant.

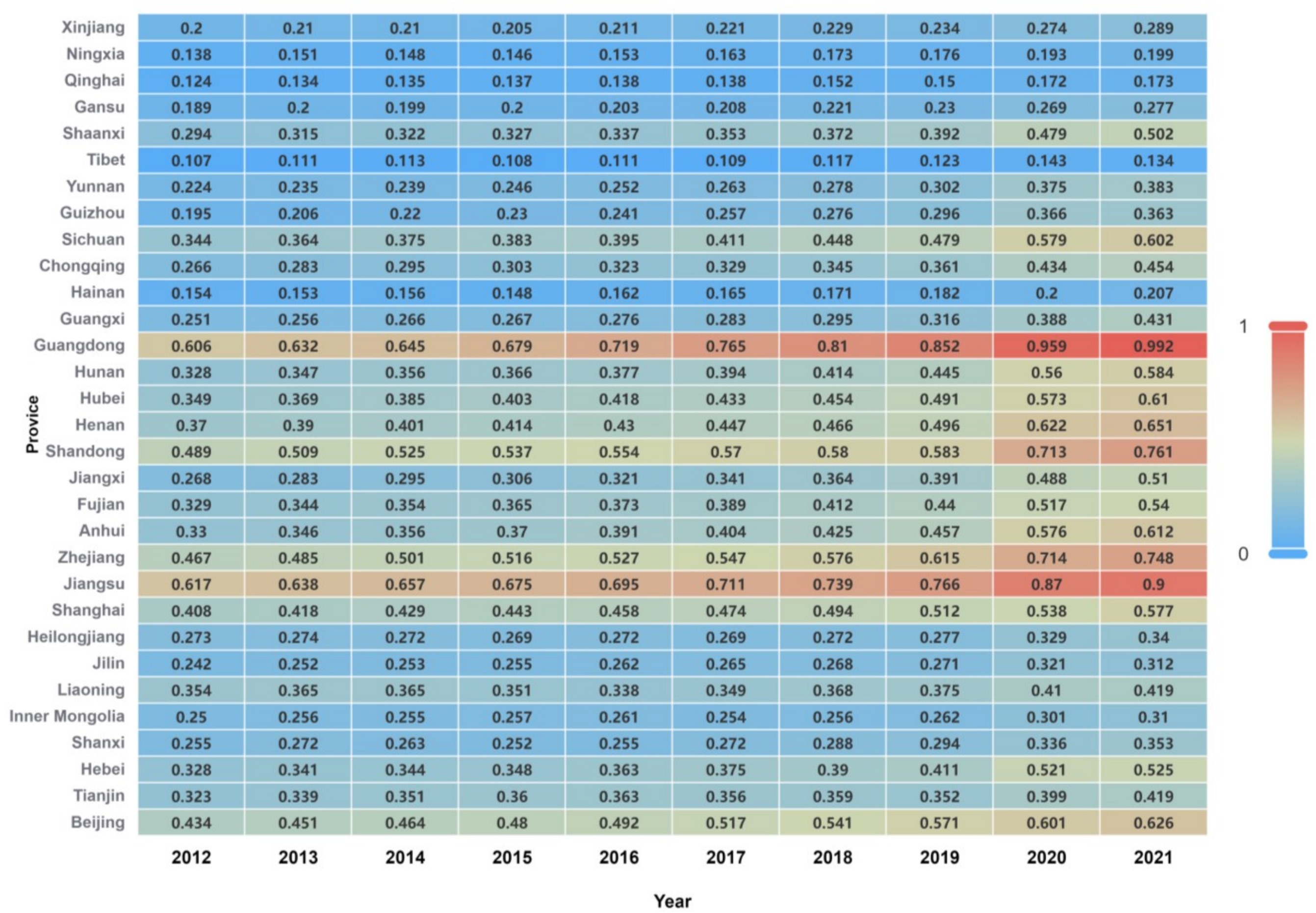
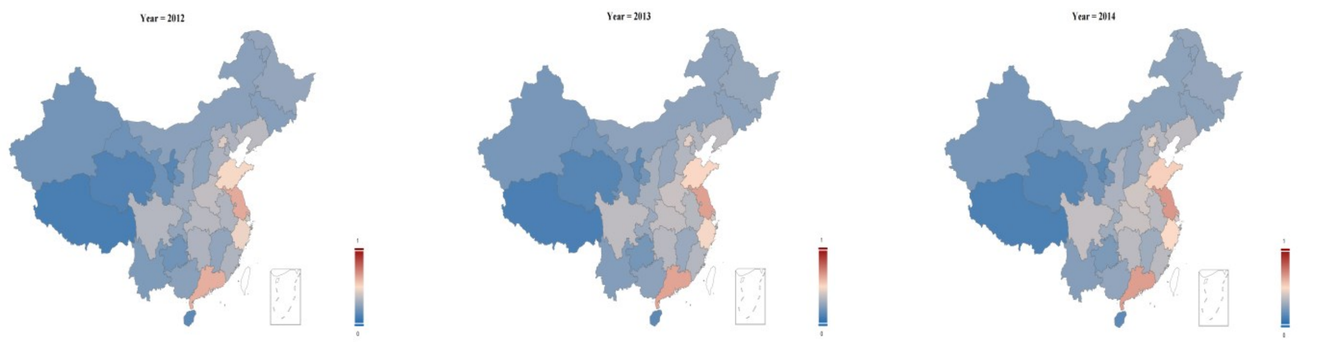
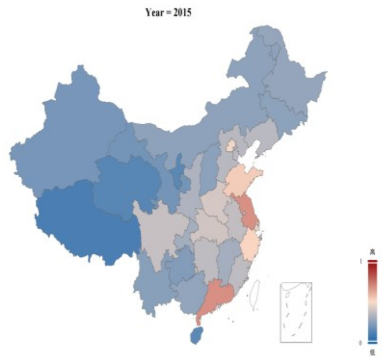


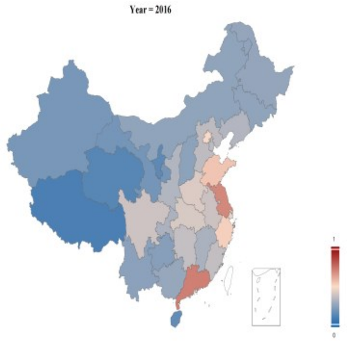
Figure 3. Heatmap of the coupling coordination degree of HVE, STI, and SED in various regions from 2012 to 2021.



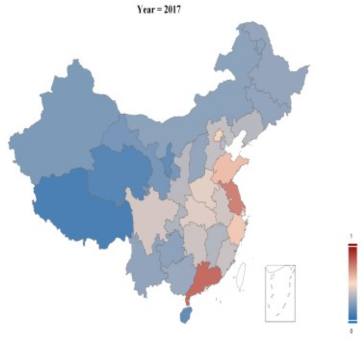
(a) Year = 2012. **(b)** Year = 2013. **(c)** Year = 2014.



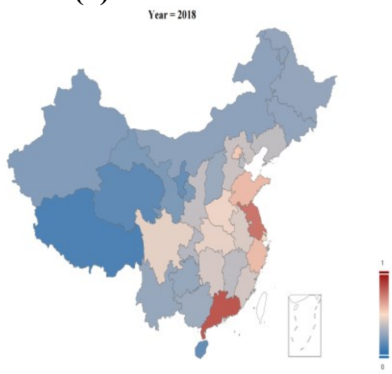
(d) Year = 2015.



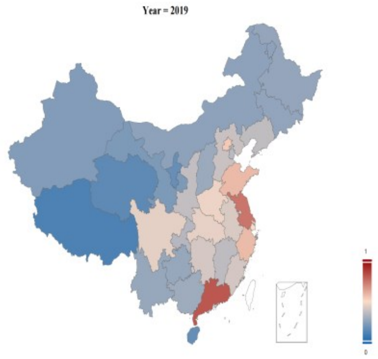
(e) Year = 2016.



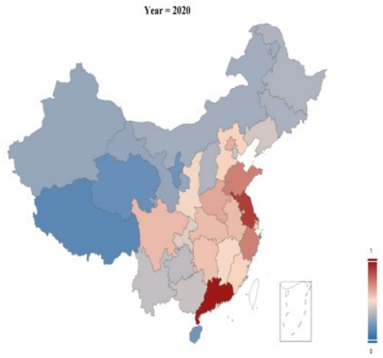
(f) Year = 2017.



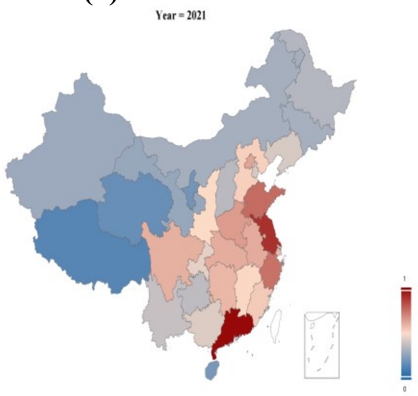
(g) Year = 2018.



(h) Year = 2019.



(i) Year = 2020.



(j) Year = 2021.

Figure 4. Spatial-temporal map of coupling and coordination degree of HVE, STI, and social-economic development in different regions from 2012 to 2021.

Table 4. Classification of coupling and coordination levels of HVE, STI, and SED of various regions from 2012 to 2021.

Province	Year									
	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Beijing	5					6			7	
Tianjin	4									5
Hebei	4							5	6	
Shanxi	3								4	
Inner Mongolia	3								4	
Liaoning	4								5	
Jilin	3								4	
Heilongjiang	3								4	
Shanghai	5							6		
Jiangsu	7					8			9	
Zhejiang	5		6					7	8	
Anhui	4					5			6	7
Fujian	4						5		6	
Jiangxi	3			4					5	6
Shandong	5	6							8	
Henan	4		5						7	
Hubei	4			5					6	7
Hunan	4						5		6	
Guangdong	7				8		9		10	
Guangxi	3							4		5
Hainan	2	3							4	
Chongqing	3			4					5	
Sichuan	4					5			6	7
Guizhou	2	3							4	
Yunnan	3							4		
Tibet	2									
Shaanxi	3	4							5	6
Gansu	2			3						
Qinghai	2									
Ningxia	2									
Xinjiang	3									

4.3. Spatial correlation test

4.3.1. Global spatial autocorrelation

The calculation results of the global Moran's I index of the coupling coordination degree and per capita GDP are shown in **Table 5**. Overall, the global Moran's I index is significantly positive, indicating that the coupling coordination degree of HVE, STI, and SED has spatial autocorrelation and spatial agglomeration effect. The global Moran's I index of per capita GDP is higher than that of the coupling coordination degree, indicating that the spatial correlation of per capita GDP is generally higher than that of the coupling coordination degree. From a temporal perspective, the global Moran's I index of the coupling coordination degree calculated based on the geographical adjacency matrix and economic distance matrix shows a small fluctuation trend, and the spatial agglomeration effect shows volatility over time. The global Moran's I index of per capita GDP calculated based on the geographical adjacency matrix shows a decreasing trend, and the spatial agglomeration effect weakens over time.

Table 5. The global Moran's I index of coupling coordination degree and per capita GDP from 2012 to 2021.

Year	Coupling coordination degree (based on geographical adjacent matrix)		Coupling coordination degree (based on economic distance matrix)		GDP per capita (based on the geographical adjacency matrix)	
	Moran's I	*P*-value	Moran's I	*P*-value	Moran's I	*P*-value
2012	0.325	0.001	0.191	0.002	0.465	0.000
2013	0.313	0.001	0.193	0.002	0.460	0.000
2014	0.325	0.001	0.197	0.002	0.444	0.000
2015	0.319	0.001	0.201	0.002	0.429	0.000
2016	0.315	0.001	0.198	0.002	0.350	0.000
2017	0.301	0.002	0.185	0.003	0.341	0.001
2018	0.286	0.003	0.174	0.005	0.342	0.001
2019	0.290	0.003	0.162	0.007	0.299	0.002
2020	0.313	0.001	0.133	0.019	0.295	0.002
2021	0.331	0.001	0.144	0.014	0.298	0.002

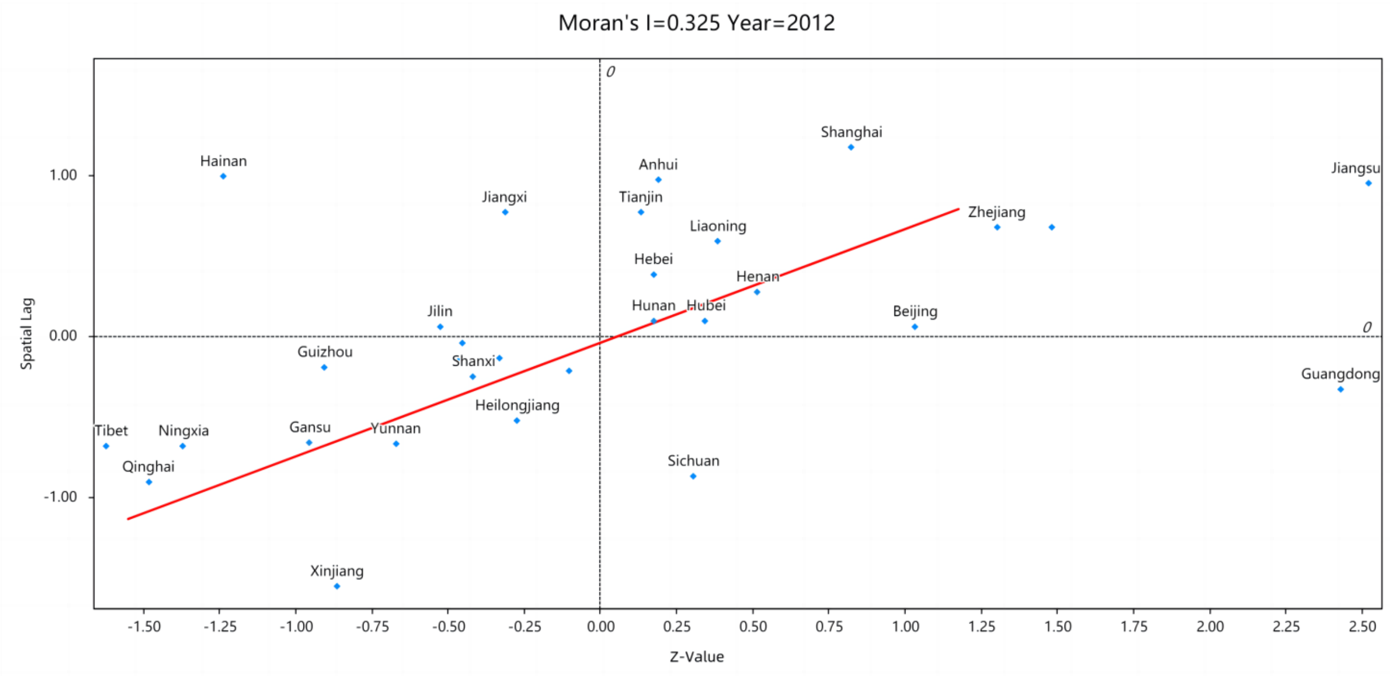
4.3.2. Local spatial autocorrelation

Through the calculation of local Moran's I index of coupling coordination, it can be seen that most regions in China belong to the agglomeration state of "high-high" or "low-low", with strong agglomeration. The measurement results based on the geographical adjacent matrix are shown in **Table 6** and **Figure 5**. The "high-high" agglomeration is the economically developed eastern and central regions, with strong spatial spillover effects. The regions of "low-high" agglomeration have low coupling coordination, but the adjacent regions have higher coupling coordination. The "low-low" agglomeration regions are mostly located in the western regions. The "high-low" agglomeration is mainly in provinces such as Guangdong and Sichuan, which have higher coupling coordination, but the adjacent provinces have lower coupling coordination, showing a "polarized" feature. The change in spatial connection form of coupling coordination reflects the development trend of regional integration. For example, Jilin, which was in the "low-high" agglomeration in 2012, entered the third quadrant of "low-low" agglomeration in 2021.

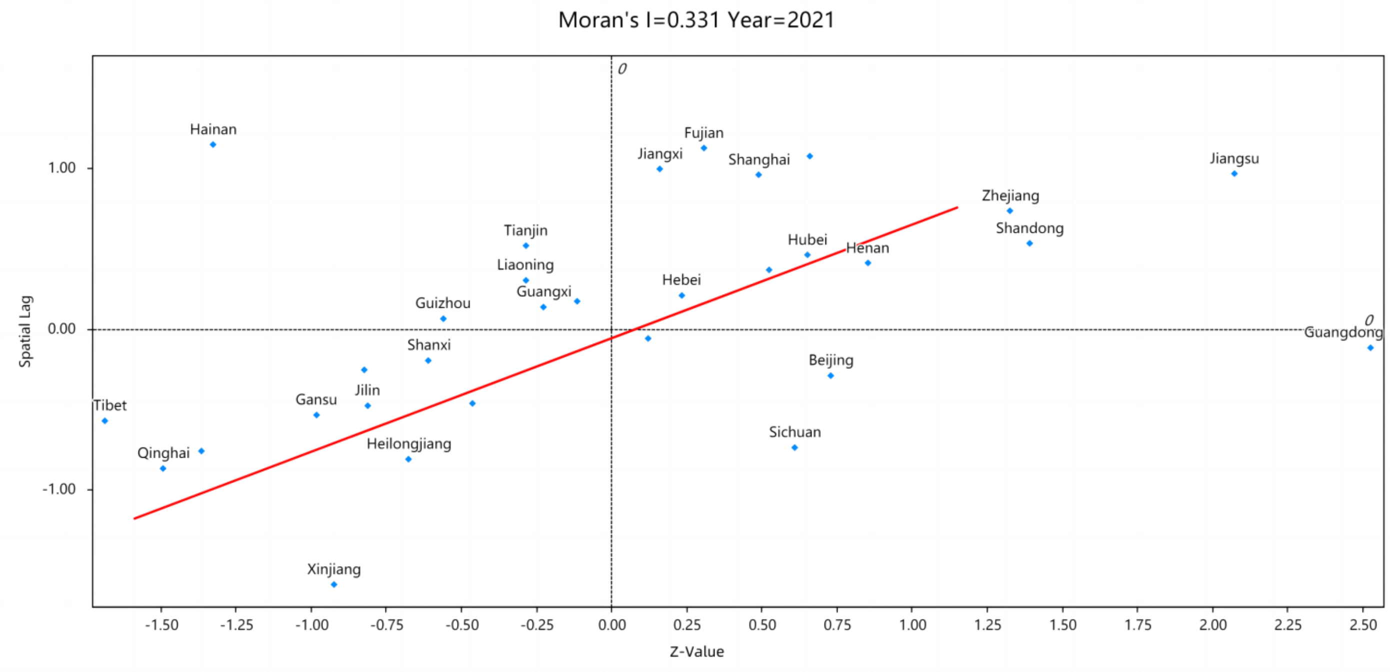
Table 6. Local spatial autocorrelation of coupling coordination degree of provinces based on geographical adjacent matrix in 2012 and 2019.

Spatial connection form	The region of 2012	The region of 2021
High-high (HH)	Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Shandong, Henan, Hubei and Hunan.	Hebei, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan
Low-high (LH)	Jilin, Jiangxi, Hainan	Tianjin, Liaoning, Guangxi, Hainan, Chongqing, Guizhou
Low-low (LL)	Shanxi, Inner Mongolia, Heilongjiang, Guangxi, Chongqing, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang	Shanxi, Inner Mongolia, Jilin, Heilongjiang, Yunnan, Tibet, Gansu, Qinghai, Ningxia, Xinjiang
High-low (HL)	Guangdong, Sichuan	Beijing, Guangdong, Sichuan, Shaanxi

In the HH region, the number of provinces showed a slightly decreasing trend, gathering in the southeastern and central regions. These regions and their surrounding areas are high-value regions, with active economic development and high-level colleges and universities. In the LH region, the number of regions doubled and distributed widely, but only Hainan did not change, indicating that its positive impact on neighboring regions has begun to increase. In 2021, Tianjin and Liaoning fell into the LH region, indicating that although the coordination level of these two regions has improved, the gap with neighboring regions has widened and their pull effect on neighboring regions is small. Guangxi, Chongqing, and Guizhou entered the HL region, indicating that while their coordination level has improved, the gap with neighboring regions has narrowed and they are more affected by neighboring regions. There are more provinces in the LL region, mostly distributed in the west and northeast, which are relatively stable. However, Jilin fell from the LH region, indicating that its pull effect on neighboring regions has not only decreased but its coordinated development has also been affected by neighboring regions. In the HL region, the number of provinces doubled but distributed widely. These regions have strong HVE, STI, and SED capabilities, and their coordination level is relatively high, but their radiation effect on neighboring regions is small. In 2021, Beijing fell into this region, indicating that although Beijing is at the primary level of coordination, its radiation and pull effect on neighboring regions is small, to some extent showing a polarization effect.



(**a**) Year = 2012.



(**b**) Year = 2021.

Figure 5. Scatter plot of local Moran's I in 2012 and 2021.

4.3.3. Regression results analysis

(1) Benchmark regression

Table 7 presents the regression results for the impact of HVE, STI, and SED on the growth of coupled coordination degrees. Columns I–III display the overall regression results for random effects, individual fixed effects, and dual fixed effects, respectively. The results indicate that per capita GDP has a significant positive effect on the growth of coupled coordination degree at the 1% level. The regression results for the eastern, central, and western regions are presented in columns IV–VI. It is observed that the per capita GDP in the eastern region has a significant negative effect on the growth of coupled coordination degree, while that in the central and western regions has a significant positive effect. As the benchmark model does not consider spatial effects, further analysis is required using the spatial Durbin model.

Table 7. Benchmark regression results.

D	I	II	III	IV	V	VI
	Random effects	**Fixed effect individual**	**Dual fixed effects**	**Eastern region**	**Central region**	**Western region**
lnPGDP	0.1534***	0.1644***	0.0959***	−0.0782*	0.1630***	0.1658***
	(10.0829)	(11.0654)	(5.3577)	(−1.7814)	(5.2754)	(6.1730)
RDP	0.0037***	0.0043***	0.0039***	0.0029***	0.0018	0.0035**
	(5.5360)	(6.2686)	(7.4258)	(4.4945)	(1.1048)	(2.0980)
RDI	7.0599***	4.7557**	2.7458*	2.3825	8.1992***	0.2597
	(3.2928)	(2.1432)	(1.6562)	(1.0092)	(3.3198)	(0.0875)
HTEC	−0.2626***	−0.3568***	−0.1942***	−0.0862	−0.1686	−0.1757
	(−3.0902)	(−4.1378)	(−2.8369)	(−0.9655)	(−1.0274)	(−1.2956)
TRADE	0.0192	0.0690*	−0.0592*	−0.2163***	0.5632***	0.3777***
	(0.5715)	(1.8273)	(−1.8617)	(−4.5496)	(2.9788)	(6.1790)
STRUC	0.2238***	0.2311***	0.2975***	−0.4540*	0.3064***	0.2859***
	(4.0529)	(4.2615)	(4.4225)	(−1.9673)	(3.2079)	(3.6366)
_cons	−1.5197***	−1.6302***	−0.8722***	1.5190***	−1.6463***	−1.6685***
	(−10.3641)	(−11.3226)	(−4.3978)	(2.6818)	(−4.9906)	(−5.6550)
ind	Yes	Yes	Yes	Yes	Yes	Yes
time	Yes	Yes	Yes	Yes	Yes	Yes
N	310	310	310	110	80	120
R^2		0.7609	0.8747	0.9099	0.9617	0.9003

(2) Spatial Durbin model regression

The results of Hausman's test and LR test indicate that the spatial Durbin model with double fixed effects should be employed for the regression analysis. **Table 8** presents the regression model based on the geographic adjacency matrix. **Table 8** indicates that GDP per capita exerts a significant positive effect on the growth of coupling coordination. The spatial lag term of GDP per capita is also significantly positive, suggesting that when GDP per capita has a positive effect on the growth of coupling coordination in geographically neighboring areas with similar levels of economic development, the effect is amplified. Second, at the level of control variables, the regression coefficients of the number of R&D personnel per 10,000 people, the ratio of R&D expenditures to GDP, the proportion of high-tech industry revenues to GDP, the proportion of imports and exports to GDP, and the proportion of tertiary industry output to GDP in the geographic proximity matrix are all significantly positive at the 1% level.

Table 8. Spatial Durbin model regression.

D	**Geographic adjacency matrix**	
	Ratio	***T*-value**
lnPGDP	0.0484**	2.5096
RDP	0.0028***	5.5759
RDI	3.9979***	2.7145
HTEC	−0.1472**	−2.3655
TRADE	−0.1208***	−4.2093
STRUC	0.2647***	4.4109
W × lnPGDP	0.0967***	3.4952
LR_Direct	0.0574***	2.9979
LR_Indirect	0.1480***	4.2916
LR_Total	0.2054***	5.7151
rho	0.2931***	4.2748
sigma2_e	0.0004***	12.1525
N	310	
R^2	0.431	

The spatial Durbin model incorporates spatial lag terms into the explanatory and interpreted variables, thereby transforming the model into a nonlinear form. Consequently, the coefficients of lnPGDP and WlnPGDP do not accurately reflect the degree of contribution of the coupling coordination degree to economic growth. To address this issue, Lesage (2008) propose calculating the direct effect, indirect effect, and total effect by solving for the bias derivatives. This approach allows for the decomposition of the effects to be summarized in a single table. The direct effect indicates a positive effect of GDP per capita on the growth of coupling coordination degree. The indirect effect reveals a significant spillover coefficient of GDP per capita in geographic space, suggesting a spatial spillover effect of GDP per capita on the coupling coordination degree.

(3) The test of regional heterogeneity based on the spatial Durbin model

HVE, STI, and SED have strong non-equilibrium characteristics, and the economic effects of coupling coordination may exist in regional heterogeneity. Therefore, the eastern, central, and western regions are grouped for regression, and the results are shown in **Table 9**. In **Table 9**, columns I–III are spatial Dubin models based on the geographical adjacent matrix, and columns IV–VI are spatial Dubin models based on the economic distance matrix. As shown in **Table 9**, firstly, the direct effect of per capita GDP in the eastern region on the growth of coupling coordination is not significant in both the geographical adjacent matrix and economic distance matrix, while the indirect effect and total effect are significantly positive. Secondly, the direct effect of per capita GDP in the central region on the growth of coupling coordination is significant in both matrices. The indirect effect is not significant in the geographical adjacent matrix but significant in the economic distance matrix. The total effect is significantly positive in the geographical adjacent matrix but not significant in the economic distance matrix. Thirdly, the direct effect of per capita GDP in the western region on the growth of coupling coordination is significant in both matrices. The indirect effect is not significant in both matrices. The total effect is significantly positive in the geographical adjacent matrix but not significant in the economic distance matrix.

Table 9. Split-sample spatial Durbin regression.

D	I	II	III	IV	V	VI
	Geographic adjacency matrix			**Economic distance matrix**		
	Eastern region	**Central region**	**Western region**	**Eastern region**	**Central region**	**Western region**
lnPGDP	0.0711	0.1081***	0.1570***	0.1203***	0.1043***	0.0717***
	(1.3626)	(3.3297)	(5.8033)	(2.6542)	(3.6206)	(2.6637)
RDP	0.0027***	0.0020	0.0035**	0.0026***	0.0022	0.0072***
	(4.8238)	(1.3528)	(2.3922)	(4.0684)	(1.3070)	(4.6656)
RDI	0.4596	6.3641**	0.7131	1.3492	5.5589*	−1.1716
	(0.2372)	(2.1349)	(0.2648)	(0.6257)	(1.7537)	(−0.4399)
HTEC	−0.0374	−0.3968*	−0.1220	−0.1018	−0.1719	0.0681
	(−0.5190)	(−1.9195)	(−0.9850)	(−1.3628)	(−0.7344)	(0.4728)
TRADE	−0.0710	0.4031**	0.2479***	−0.1001**	0.4006**	0.2284***
	(−1.5474)	(2.2426)	(3.7996)	(−2.1016)	(2.4086)	(3.6697)
STRUC	−0.0261	0.1357	0.3507***	0.2276	0.2500**	0.2246***
	(−0.1221)	(1.3308)	(4.7577)	(1.1724)	(2.0306)	(3.5240)
W × lnPGDP	0.2089***	−0.0291	−0.0235	0.6544***	−0.1437*	−0.1647
	(2.6170)	(−0.7402)	(−0.4212)	(3.4153)	(−1.7311)	(−0.9576)
rho	−0.3199***	0.0012	−0.1996	−1.0757***	−0.3178	−0.2071
	(−2.8820)	(0.0127)	(−1.4615)	(−4.6627)	(−1.5326)	(−0.7856)
sigma2_e	0.0003***	0.0001***	0.0002***	0.0003***	0.0001***	0.0002***
	(6.8613)	(6.3246)	(7.7364)	(6.6109)	(6.3968)	(7.7733)
LR_Direct	0.0470	0.1093***	0.1606***	0.0492	0.1169***	0.0748**
	(0.9596)	(3.2439)	(5.5717)	(1.2738)	(3.6239)	(2.4956)
LR_Indirect	0.1708**	−0.0299	−0.0498	0.3340***	−0.1469**	−0.1694
	(2.4072)	(−0.7822)	(−1.0604)	(2.7597)	(−2.0250)	(−0.9944)
LR_Total	0.2178**	0.0794**	0.1108**	0.3833***	−0.0300	−0.0946
	(2.1033)	(2.2753)	(2.5044)	(2.7711)	(−0.4628)	(−0.5445)
N	110	80	120	110	80	120
R^2	0.122	0.533	0.286	0.028	0.640	0.591

It can be seen that the coupling and coordination degree of HVE, STI, and SED in the eastern, central, and western regions can all produce significant economic effects, but the specific effect directions and decomposition situations are different, which means that the economic effects of coupling coordination degree have regional heterogeneity.

4.3.4. Robustness tests

(1) Replacement of spatial matrix robustness test

In order to ensure the robustness of the empirical results, this paper employs the replacement method for the spatial weight matrix in the robustness test and the economic distance matrix in the regression analysis. The results are presented in **Table 10**.

Table 10. Robustness test based on economic distance matrix.

D	**Economic distance matrix**	
	Ratio	***T*-value**
lnPGDP	0.0676***	3.2699
RDP	0.0035***	6.2027
RDI	2.3916	1.4596
HTEC	−0.2233***	−3.3901
TRADE	−0.0263	−0.8182
STRUC	0.2265***	3.2189
W × lnPGDP	0.3186***	2.601
LR_Direct	0.0760***	3.5151
LR_Indirect	0.5076**	2.1979
LR_Total	0.5836**	2.4989
rho	0.3130*	1.8479
sigma2_e	0.0005***	12.2919
N	310	
R^2	0.451	

The comparison indicates that the size, direction, and significance level of the regression coefficients of the explanatory variables have not undergone a significant change. While the significance of some variables has altered, the direction of the coefficients remains consistent. Overall, the results obtained after replacing the matrix are largely consistent with those before replacement, suggesting that the findings of this paper are robust when considering the spatial matrix.

(2) Robustness test with replacement of sample size

In order to consider the model's robustness from multiple perspectives, this paper also conducts a robustness analysis from the perspective of sample size. After excluding the sample data from 2012 and 2013, the results are presented in **Table 11**.

Table 11. Robustness tests for sample size replacement.

D	**Geographic adjacency matrix**	
	Ratio	***T*-value**
LnPGDP	0.0496**	2.2067
RDP	0.0045***	7.7102
RDI	1.2543	0.7113
HTEC	−0.2035***	−2.8359
TRADE	−0.0625	−1.4115
STRUC	0.2186***	2.7988
W × PGDP	0.2865*	1.9167

Table 11. (*Continued*).

D	**Geographic adjacency matrix**	
	Ratio	***T*-value**
rho	0.2701	1.3822
sigma2_e	0.0004***	11.1877
LR_Direct	0.0563**	2.4199
LR_Indirect	0.4242*	1.7341
LR_Total	0.4804*	1.9558
N	248	
fR^2	0.457	

A comparison of the regression coefficients of the explanatory variables reveals that the size, direction, and significance level have not changed significantly. However, the significance of some variables has changed, yet the direction of the coefficients remains consistent. Overall, the results obtained after replacing the sample size are comparable to those before replacement, indicating that the findings of this paper are robust with respect to the sample size.

4.4. Grey model analysis

4.4.1. Grey correlation analysis results

To further analyze the reasons for the differences in the coupling coordination across China, a gray correlation analysis was used to analyze the correlation between influencing factors of national correlation and the mother coupling coordination degree, to explore the impact of these factors on the overall coupling coordination of the country.

Based on existing literature research and data availability (Li et al., 2021), the coupling coordination degree was determined using 21 feature sequences that influence national coupling coordination. First, the data was processed without scaling, and then the correlation coefficient and gray correlation degree of each index were calculated. Then the Pearson correlation analysis was used to calculate the positive and negative correlations between the influencing factors and national coupling coordination. Finally, the main factors that affect national coupling coordination were determined by combining gray correlation rankings with correlation coefficients. **Table 12** shows the results of the correlation between each influencing factor and the national coupling coordination degree.

It can be seen from **Table 12** that among the factors that affect the coupling coordination of the whole country, the technical market contract amount, financial expenditure on science and technology, the number of patent applications authorized, the output value of the tertiary industry, and the number of research and development institutions rank in the top five, while the number of full-time teachers, the number of students, the number of schools, the level of residents' consumption, and the fixed asset investment of the whole society rank in the last five. Among the influencing factors, the most significant correlation indicators are R&D funding, the number of full-time teachers, GDP, per capita GDP, the number of schools, the output value of the tertiary industry, the number of research and development institutions, local fiscal revenue, full-time equivalent R&D personnel, and national fiscal education funding. The rankings of their coupling coordination correlation degrees with the whole country are similar. It can be seen that the above indicators are the factors that affect the heterogeneity of national coupling coordination.

Table 12. The grey relational degree and correlation coefficient of influencing factors and coupled coordination.

Related factors	Correlation coefficient	Relevance	Sorting	Related factors	Correlation coefficient	Relevance	Sorting
Number of students	0.837**	0.546	18	The amount of the signed contract in the technology market	0.943**	0.625	1
Number of schools	0.983**	0.543	19	The main business income of the high-tech industry	0.968**	0.562	10
Number of full-time teachers	0.969**	0.564	9	GDP	0.985**	0.560	12
The total investment of scientific research funds in higher vocational colleges	0.989**	0.546	17	Per capita GDP	0.985**	0.557	13
State financial expenditure on education	0.958**	0.570	6	The level of residents' consumption	−0.340	0.539	20
The value of teaching instruments and equipment in higher vocational colleges	0.940**	0.570	8	The fixed assets investment of the whole society	0.748*	0.406	21
The full-time equivalent of R&D personnel	0.970**	0.553	14	Total import and export trade volume	0.773**	0.546	16
Number of R&D institutions	0.978**	0.574	5	Local fiscal revenue	0.976**	0.562	11
R&D expenditure	0.990**	0.570	7	The output value of the secondary industry	0.965**	0.551	15
Financial expenditure on science and technology	0.966**	0.585	2	The output value of the tertiary industry	0.982**	0.574	4
The number of authorized patents	0.922**	0.576	3				

4.4.2. The result of gray prediction GM(1,1)

Table 13 shows the coupling coordination degree of various regions from 2022 to 2025, calculated using the results of the grey prediction GM(1,1) model (Liu et al., 2016).

As shown in **Table 13**, compared to 2021, the coupling coordination degree of HVE, STI, and SED in China has increased to a certain extent from 2022 to 2025. Some regions have achieved level jumps to the middle or high-level stages, but there are still some regions that remain at the low-level stage. It can be seen that the improvement of the coupling coordination degree is a relatively long process, and it is difficult to achieve a significant leap in the short term. The differences among regions are still obvious. In 2025, the coupling coordination degrees of all regions were classified by grades, and the results are shown in **Table 14**. As shown in **Table 14**, there are 16 regions with coupling coordination degrees above the barely coordinated level, an increase of 1 compared to 2021. The regions that have reached the coordinated level are mainly in the eastern coast region, while the regions at the dysfunctional level are mostly in central and western regions, with most having lower coupling coordination degrees.

Table 13. Predicted results of coupling coordination degree in various regions from 2022 to 2025.

Province	2022	2023	2024	2025	Province	2022	2023	2024	2025
Beijing	0.649	0.677	0.707	0.738	Hubei	0.628	0.67	0.715	0.764
Tianjin	0.406	0.414	0.423	0.432	Hunan	0.581	0.615	0.649	0.684
Hebei	0.526	0.552	0.579	0.606	Guangdong	1	1	1	1
Shanxi	0.349	0.363	0.378	0.394	Guangxi	0.412	0.433	0.455	0.478
Inner Mongolia	0.3	0.307	0.314	0.322	Hainan	0.211	0.22	0.23	0.239
Liaoning	0.41	0.418	0.426	0.435	Chongqing	0.455	0.477	0.5	0.524
Jilin	0.317	0.326	0.336	0.347	Sichuan	0.607	0.642	0.677	0.713
Heilongjiang	0.327	0.336	0.346	0.355	Guizhou	0.379	0.402	0.425	0.448
Shanghai	0.586	0.609	0.634	0.66	Yunan	0.385	0.405	0.426	0.448
Jiangsu	0.915	0.957	1	1	Tibet	0.139	0.143	0.148	0.152
Zhejiang	0.766	0.811	0.859	0.911	Shaanxi	0.498	0.524	0.55	0.577
Anhui	0.608	0.645	0.683	0.722	Gansu	0.279	0.292	0.306	0.321
Fujian	0.555	0.59	0.628	0.667	Qinghai	0.176	0.182	0.189	0.195
Jiangxi	0.516	0.548	0.581	0.614	Ningxia	0.204	0.213	0.222	0.231
Shandong	0.74	0.772	0.804	0.837	Xinjiang	0.286	0.299	0.313	0.327
Henan	0.648	0.684	0.721	0.76					

Table 14. The coupling coordination degree of various regions in 2025.

Coupling coordination levels	The interval of coupling coordination degree *D* value	Coordination level	The degree of coupling coordination	Including regions
Low-level (disorderly development)	[0.1~0.2)	2	Serious imbalance	Tibet, Qinghai
	[0.2~0.3)	3	Moderate imbalance	Hainan, Ningxia
Middle-level (transitional development)	[0.3~0.4)	4	Mild disorder	Shaanxi, Inner Mongolia, Jilin, Heilongjiang, Gansu, Xinjiang
	[0.4~0.5)	5	Borderline disorder	Tianjin, Liaoning, Guangxi, Guizhou and Yunnan
	[0.5~0.6)	6	Strenuously coordinated	Chongqing, Shaanxi
	[0.6~0.7)	7	Primary coordination	Hebei, Shanghai, Fujian, Jiangxi and Hunan
High-level (coordinated development)	[0.7~0.8)	8	Intermediate coordination	Beijing, Anhui, Henan, Hubei and Sichuan
	[0.8~0.9)	9	Good coordination	Shandong
	[0.9~1.0)	10	Coordination of high quality	Jiangsu, Zhejiang and Guangdong

5. Conclusions and discussion

5.1. Conclusions

This paper employs panel data from 31 provinces in China from 2012 to 2021 to calculate the coupling coordination degree of HVE, STI, and socio-economic development. The spatial aggregation effect is then verified by using Moran's index. Finally, the paper employs gray correlation analysis to explore the indicators affecting the degree of coupling coordination and makes predictions for the situation in 2022–2025. The principal findings are as follows:

The degree of coupling coordination demonstrates an upward trend. By calculating the degree of coupling coordination, this study reveals a macro upward trend in the degree of coupling coordination between HVE, science and technology innovation, and social and economic development in China from 2012 to 2021. This upward trend not only reflects an increase in the interaction force among the three, but also indicates that the synergistic effect of education, science and technology, and economic policies is gradually emerging. However, this growth is not evenly distributed across the country, and the spatial distribution characteristics are evident, suggesting the need to consider regional differences in future policy formulation.

The presentation of regional development is balanced. It is found that the spatial distribution of the coupling coordination degree presents a significant pattern of high in the east and low in the west, and higher in the coast than in the inland. This phenomenon may be attributed to the imbalance in the level of regional economic development, as well as the geographical differences in educational resources and STI capabilities. The eastern coastal region has a leading advantage in coupling coordination degree due to its earlier economic development, rich educational resources, and active STI.

There is significant heterogeneity in the growth of regional coupling coordination degree. The impact of socio-economic development on the coupling coordination degree shows significant heterogeneity in different regions. GDP per capita in the eastern region is negatively correlated with the growth of coupling coordination degree, which may be related to the maturity of the economic structure and the transformation needs of the region. Conversely, GDP per capita in the central and western regions exerts a positive influence on the growth of coupling coordination degree, suggesting that economic development continues to serve as a pivotal driving force for education and STI in these regions.

The key factors affecting the degree of coupling coordination exist objectively. Through a grey correlation analysis, it was found that the amount of contracts transacted in the technology market, financial expenditure on science and technology, the amount of patent applications and authorizations, the output value of the tertiary industry, and the number of research and development institutions are the main factors influencing the differences in the coupling degree of coordination. A common feature of these factors is their close correlation with science and technology innovation and market mechanisms. This emphasizes the core role of science and technology innovation in promoting education and economic development.

The future growth of the degree of coupling and coordination is expected to be long-term in nature. The results of the gray prediction model indicate that although the coupling and coordination degree is expected to continue to rise during the period of 2022–2025, there are still a limited number of regions that have reached the primary coordination status. This prediction suggests that the improvement in coupling and coordination will be gradual and long-term, and that achieving a significant leap in the short term may be challenging.

5.2. Discussion

The National Implementation Program for Vocational Education Reform facilitates the profound integration of vocational education and social economy. A comprehensive examination of the National Implementation Program for Vocational Education Reform reveals a clear determination and strength on the part of the State in its reform of vocational education. The program not only delineates a direction for the development of vocational education but also promotes the in-depth integration of vocational education with the social economy from the policy level. The results of the study indicate that the coupling and coordination of HVE and social and economic development have been enhanced, thereby exemplifying the deep integration. This integration is not a simple superposition, but rather an organic combination of vocational education and social economy at multiple levels and dimensions. Vocational education must not only cultivate students' professional skills but also focus on their comprehensive quality and innovation ability. This is necessary to adapt to the rapid development of the social economy and the ever-changing market demand. Furthermore, this integration promotes the development of the social economy and provides society with more high-quality and high-skilled human resources.

The integration of industry and education represents a crucial step towards the realization of a mutually beneficial development of both the education and industry chains. The integration of industry and education represents a pivotal direction within the current education reform movement, serving as a pivotal pathway for the advancement of high-quality vocational education. Our research findings indicate that the integration of industry and education has yielded considerable outcomes. The growth in the amount of contracts transacted in the technology market, the increase in financial expenditure on science and technology, and the increase in the number of patent applications and authorizations are all concrete results of the in-depth implementation of the policy of integration of industry and education. This integration mode not only effectively promotes the transformation and application of STI achievements, but also provides HVE with teaching content and practice platforms that are closer to reality and more targeted. The integration of industry and education has facilitated the organic articulation of the education and industrial chains. This articulation has not only enhanced the quality and effectiveness of vocational education but also provided robust talent support and intellectual guarantee for the upgrading and transformation of the industrial chain.

The challenge of regional coordination and balance in the context of high-quality development presents both challenges and opportunities. In light of the demands of the era of high-quality development, it is imperative to address the issue of imbalance in the degree of coupled coordination between regions. This imbalance is evident in the discrepancies between the eastern, central, and western regions, as well as between urban and rural areas and between different types of regions. This imbalance is the consequence of a confluence of factors, including the level of economic development, the distribution of educational resources, policy orientation, and so forth. However, challenges and opportunities often coexist. This imbalance provides us with more room for development and more impetus for reform. In the future, it is necessary to promote the balanced development of vocational education and science, technology, and innovation in all regions through more precise policy formulation and implementation in order to achieve nationwide coordination and balance. This necessitates a focus on not only the leading role of the developed eastern regions, but also on the latecomer advantages of the central and western regions and less developed regions. It is essential to provide these regions with the necessary policy inclination and resource support to enable them to catch up and achieve common development.

The role of science and technology innovation in the reform of vocational education: The advancement of science and technology represents a pivotal catalyst for the integration and alignment of HVE with the advancement of social and economic development. This is a central tenet of our study. Science and technology innovation not only furnishes vocational education with cutting-edge instructional resources and practical training facilities, but also expands the scope and potential for the advancement of vocational education through the guidance of industrial advancement and the promotion of social progress. Concurrently, STI necessitates that vocational education continuously update its teaching content and teaching methods to align with the pace of scientific and technological advancement and shifts in market demand. Consequently, it is of paramount importance to accord the leading role of STI in the reform of vocational education. This can be achieved through a number of measures, including increased investment in scientific and technological research and development, the promotion of the transformation and application of scientific and technological achievements, and the fostering of innovative talents. These measures will continue to improve the quality and level of vocational education, thereby providing a strong guarantee of talents and intellectual support for the development of the social economy.

5.3. Innovation and limitations

This article is innovative in three aspects. First, multiple indicators are selected to establish a comprehensive evaluation model of coupling coordination degree, which examines the relationship among HVE, STI, and SED from the perspective of system coupling. Second, Moran's index and spatial Durbin model are used to test spatial correlation and analyze spatial differences. Third, the gray model is applied to predict the situation from 2022 to 2025 based on gray correlation analysis.

However, there are still some limitations in this article. First, limited by the availability of data, the persuasiveness and representativeness of indicators need to be strengthened. At the same time, the sample years end in 2021, which fails to fully reflect the latest progress of various regions. Second, due to data quality, objective conditions, and other restrictions, there are certain limitations in data analysis. It has not yet comprehensively analyzed data from multiple dimensions and levels. Third, the relationship between HVE and the supply of high-quality technical skilled talents, as well as the integration of production and education, needs further research.

5.4. Policy recommendations and prospects

In light of the findings and conclusions of the current study, the following policy recommendations are put forth: Firstly, it is recommended that the government continue to increase its investment in HVE, optimise the mechanism for allocating educational resources, and ensure that the infrastructure of vocational education and the construction of teaching staff are adequately safeguarded. Secondly, it is proposed that the policy of integration of industry and education be further implemented, and that vocational colleges and universities, enterprises, and industries engage in closer cooperation and exchanges in order to realise the sharing of resources and the complementation of each other's strengths. Firstly, it is necessary to enhance the complementarity of the strengths of each party involved; secondly, to reinforce the coordination and cooperation between regions, with the objective of achieving balanced development of vocational education across the country; thirdly, to reinforce the application and promotion of STI in vocational education, with the objective of encouraging vocational colleges and universities to engage in scientific and technological research and development activities, and to participate actively in market competition, cooperation and exchanges. In the future, it is anticipated that a favorable ecological environment will be established for the joint development of vocational education and the social economy. This will be achieved through the implementation of appropriate policies that will provide a solid foundation for the long-term development of the country, in terms of both talent and intellectual resources.

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References

An, Z., He, E., Du, X., et al. (2024). Path analysis of regional logistics and economy coordinated development: An fsQCA approach. PLOS ONE, 19(2), e0297441. https://doi.org/10.1371/journal.pone.0297441

Cai, W., Chen N., & Shi, H. (2022). An Empirical Study on Coupling Coordination Between Higher Education Investment and Economic Growth in Chengdu—Chongqing Economic Circle. Heilongjiang Researches on Higher Education, (02), 46–53. https://doi.org/10.19903/j.cnki.cn23-1074/g.2022.02.007

Chen, J. (2020). Research on Fit Degree Between Specialties Setting of Higher Vocational Education and Regional Industrial Development under Background of High-quality Development——A Case Study of Guangzhou Municipal Higher Vocational Colleges. Vocational and Technical Education, (20), 31–35. https://doi.org/CNKI:SUN:ZYJW.0.2020-20-007

Chen, J., & Wang, F. (2021). Research on the Fit between Specialty Setting of Higher Vocational Education and Regional Industrial Structure in Guangdong-HongKong-Macao Greater Bay Area from the Perspective of Industry-education Integration. Education and Vocation, (17), 34–39. https://doi.org/10.13615/j.cnki.1004-3985.2021.17.005

Cheng, Z., Zhao, T., Zhu, Y., & Li, H. (2022). Evaluating the Coupling Coordinated Development between Regional Ecological Protection and High-Quality Development: A Case Study of Guizhou, China. Land, 11(10), 1775. https://doi.org/10.3390/land11101775

Fu, S., Liu, J., Wang, J., et al. (2023). Enhancing urban ecological resilience through integrated green technology progress: evidence from Chinese cities. Environmental Science and Pollution Research, 31(25), 36349–36366. https://doi.org/10.1007/s11356-023-29451-3

Gao, Z. G., Zhi, Y., & Han, Y. L. (2023). Research on the impact of science and technology innovation on the high-quality development of China's regional economy—A measurement analysis based on data on the development level of 30 provinces from 2009 to 2018. China University Science & Technology, (03), 14–21. https://doi.org/10.16209/j.cnki.cust.2023.03.032

Geng, M., & Tian H. (2023). The Coupling and Coordination between Higher Education and Industry and Its Economic Effect: An Empirical Analysis Based on the Provincial Panel Data and Spatial Dubin Model. Chongqing Higher Education Research, (03), 64–78. https://doi.org/10.15998/j.cnki.issn1673-8012.2023.03.005

Geng, Y. Q., Chen, L. Y., Li, J. Y., & Iqbal, K. (2023). Higher education and digital Economy: Analysis of their coupling coordination with the Yangtze River economic Belt in China as the example. Ecological Indicators, 154, 110510. https://doi.org/10.1016/j.ecolind.2023.110510

Geng, Y., & Yan, Y. (2021). Higher education and science popularization: Can they achieve coordinated growth? PLOS ONE, 16(9), e0256612. https://doi.org/10.1371/journal.pone.0256612

Geng, Y., Chen, L., Li, J., & Iqbal, K. (2023). Higher education and digital economy: Analysis of their coupling coordination with the Yangtze River economic belt in China as the example. Ecological Indicators, 154, 110510. https://doi.org/10.1016/j.ecolind.2023.110510

Guo, X. J., Li, J. Q., Ma, Y. J., et al. (2023). Study on the Coupling and Coordination between Urban Resilience and Low-Carbon Development of Central Plains Urban Agglomeration. Sustainability, 15(24), 16748. https://doi.org/10.3390/su152416748

Han, D., Chen, L., Wu, H., et al. Evaluation on coupling coordinated development of population economy and eco-geological environment in the twin-city economic circle of Chengdu—Chongqing region. Scientific Reports, 13(1). https://doi.org/10.1038/s41598-023-40352-w

Han, X., Fu, L., Lv, C., & Peng, J. (2023). Measurement and spatio-temporal heterogeneity analysis of the coupling coordinated development among the digital economy, technological innovation and ecological environment. Ecological Indicators, 151, 110325. https://doi.org/10.1016/j.ecolind.2023.110325

Han, Y., Ni, R., Deng, Y., et al. (2023). Supply and demand of higher vocational education in China: Comprehensive evaluation and geographical representation from the perspective of educational equality. PLOS ONE, 18(10), e0293132. https://doi.org/10.1371/journal.pone.0293132

Hu, R. F., & Xu, W. Q. (2022). Exploring the Technological Changes of Green Agriculture in China: Evidence from Patent Data (1998–2021). Sustainability, 14(17), 10899. https://doi.org/10.3390/su141710899

Huang, Z., Fan, S., Zhou, Y., et al. (2023). The collaborative development of graduate education and high economic quality and its dynamic evolution forecast. Heliyon, 9(11), e21438. https://doi.org/10.1016/j.heliyon.2023.e21438

Jiang, J., & Zhang, Y. (2023). Empirical Study on the Coupling between Specialty Cluster Setting and Industrial Structure of Higher Vocational Education in Jiangsu. Vocational and Technical Education, (23), 36–41. https://doi.org/CNKI:SUN:ZYJW.0.2023-23-006

Lesage, J. P. (2008). Introduction to spatial econometrics. Varia, 1223, 19–44. https://doi.org/10.4000/rei.3887

Li, H. J., & Liu, S. (2021). Higher Education, Technological Innovation, and Regional Sustainable Development: Insights from a VAR Model. Discrete Dynamics in Nature and Society, 2021, 8434528. https://doi.org/10.1155/2021/8434528

Li, W., & Yi, P. (2020). Assessment of city sustainability—Coupling coordinated development among economy, society and environment. Journal of Cleaner Production, 256, 120453. https://doi.org/10.1016/j.jclepro.2020.120453

Li, X., Fang, B., Yin, M., et al. (2022). Multi-Dimensional Urbanization Coordinated Evolution Process and Ecological Risk Response in the Yangtze River Delta. Land, 11(5), 723.

Li, Y., Luo, D., Chen, L., et al. (2021). Study on the Influencing Factors and Countermeasures of Tourism Development in Sanya City Based on Grey Relational Analysis. In: Zeng, J., Qin, P., Jing, W., et al. (editors). ICPCSEE 2021—Communications in Computer and Information Science. Springer, Singapore. https://doi.org/10.1007/978-981-16-5943-0_28

Lin, S. (2022). Research on the Adaptability Between Specialty Setting and Industrial Structure in Guangdong Higher Vocational Colleges. Education and Vocation, (11), 46–50. https://doi.org/10.13615/j.cnki.1004-3985.2022.11.014

Liu, H., & Liu, Z. (2024). On the Spatiotemporal Evolution of the Integration of Industry and Education in Higher Vocational Education under the Background of High-Quality Development. Research in Higher Education of Engineering, (01), 151–157. https://doi.org/CNKI:SUN:GDGJ.0.2024-01-024

Liu, X. F., & Ma, L. (2023). Sustainable Development of Business Economy Based on Big Data Algorithm under the Background of Low-Carbon Economy. Sustainability, 15(7), 5840. https://doi.org/10.3390/su15075840

Liu, X., & Chen, L. (2022). Research on the Adaptability of Specialty Set-up in Higher Vocational Colleges upon Industrial

Structure—An Empirical Study Based on 14 Higher Vocational Colleges in Hainan. Vocational and Technical Education (35), 33–39. https://doi.org/CNKI:SUN:ZYJW.0.2022-35-006
Liu, X., Yang, J., Chen, L., & Chen, M. (2016). Prediction for air route passenger flow based on a grey prediction model. In: Proceedings of the 2016 International Conference on Cyber-Enabled Distributed Computing and Knowledge Discovery (CyberC). pp. 185–190. https://doi.org/10.1109/CyberC.2016.45
Ma, W. (2022). Research on the coupling and coordination of green finance, higher education, and green economic growth. Environmental Science and Pollution Research, 29(39), 59145–59158.
Pan, H., & Weng, X. (2021). A study on the coupling relationship between higher vocational education and economic and social development in China: based on the panel data of 31 provinces from 2006 to 2018. Journal of Higher Education Management, (02), 12–23. https://doi.org/10.13316/j.cnki.jhem.20210206.002
Peng, S. L., & Wu, M. Y. (2021). Research on the coupled and coordinated development of higher education scale and regional economy in China. Statistics & Decisiong, (09), 109–112. https://doi.org/10.13546/j.cnki.tjyjc.2021.09.025
Ren, X., & Zhou, Y. (2022). Coupling and coordinated development of higher vocational education and economic development in the Yangtze River economic belt from 2008 to 2020. Computational Intelligence and Neuroscience, 2022, 1–13. https://doi.org/10.1155/2022/2643635
Shi, H. (2023). Research on the Coupling Coordination Development of Provincial Higher Education and Digital Economy in China. Chongqing Higher Education Research, (06), 90–102. https://doi.org/10.15998/j.cnki.issn1673-8012.2023.06.009.23
Song, M., & Li, M. (2019). The Coupling Degree and Its Determinants of Higher Education, Scientific and Technological Innovation and Economic Development in China. Modern Education Management, (03), 19–25. https://doi.org/10.16697/j.cnki.xdjygl.2019.03.004
Sun, F., Shan, Y., Tian, Y., & Lv, Z. (2023). The Coupling and Coordination Relationship and Characteristics of Vocational Education Scale and Regional Economic Development—Analysis Based on Panel Data of 31 Provinces from 2014 to 2020. Contemporary Vocational Education, (01), 35–45. https://doi.org/10.16851/j.cnki.51-1728/g4.2023.01.007
Tao, H., & Liao, H. (2016). Research on the Docking between Professional Setting and Industrial Structure of Higher Vocational Colleges in Guangdong Province. Vocational & Technical Education Forum, (18), 40–44. https://doi.org/CNKI:SUN:ZJLT.0.2016-18-008
Tao, H., & Shan, L. (2019). Study on the Specialty Setting of Vocational Colleges and Industrial Structure Adaptability in Guangdong-Hong Kong-Macao Greater Bay Area. Journal of Vocational Education, (09), 126–131. https://doi.org/CNKI:SUN:ZJLT.0.2019-09-023
Wang, H, & Su, B. (2023). Research on the Coupling and Coordination of Science and Technology Innovation of Higher Education Institutions and Regional Economy and Influencing Factors—Based on the Relevant Data of 30 Provinces in China from 2013–2019. China University Science & Technology, (06), 37–43. https://doi.org/10.16209/j.cnki.cust.2023.06.017
Wang, H., & Tang, Y. Spatiotemporal Distribution and Influencing Factors of Coupling Coordination between Digital Village and Green and High-Quality Agricultural Development—Evidence from China. Sustainability, 2023, 15, 8079. https://doi.org/10.3390/ su15108079
Wang, J., Shi, X., & Du, Y. (2021). Exploring the relationship among marine science and technology innovation, marine finance, and marine higher education using a coupling analysis: a case study of China's coastal areas. 132, 104706. https://doi.org/10.1016/j.marpol.2021.104706
Wang, M., Zhu, X., & Yin, S. Spatial-temporal coupling coordination and interaction between digitalization and traditional industrial upgrading: A case study of the Yellow River Basin. Scientific Reports, 13(1). https://doi.org/10.1038/s41598-023-44995-7
Wei, Y., Xuan, M., & Liao, D. (2023). Analysis of the Adaptability of the Professional Structure of Agricultural Vocational Education—Based on the Transformation and Upgrading Development of Guangxi's Agricultural Industrial Structure. Social Scientist, (08), 155–160.
Wu, L. R., & Chen, W. (2023). Technological achievements in regional economic development: An econometrics analysis based on DEA. Heliyon, 9(6), e17023. https://doi.org/10.1016/j.heliyon.2023.e17023
Xu, H. Y., Hsu, W. L., Meen, T. H., & Zhu, J. H. (2020). Can Higher Education, Economic Growth and Innovation Ability Improve Each Other? Sustainability, 12(6), 2515. https://doi.org/10.3390/su12062515
Xu, S., & Xu, D. (2022). On the Regional Industrial Adaptability of Vocational Education Under the Associated Logic——An

Empirical Case from Ningbo City. Education Research Monthly, (09), 68–74. https://doi.org/10.16477/j.cnki.issn1674-2311.2022.09.009

Yang, J., & Cheng, H. D. (2023). Coupling Coordination between University Scientific & Technological Innovation and Sustainable Economic Development in China. Sustainability, 15(3), 2494. https://doi.org/10.3390/su15032494

Ye, C. (2020). Research on Coupling Coordination Development between Scale of Higher Vocational Education and Regional Economy—An Empirical Analysis Based on Panel Data of 12 Provinces (Municipality and Autonomous Regions) in Western China. Vocational and Technical Education, (21), 51–56. https://doi.org/CNKI:SUN:ZYJW.0.2020-21-012.46

You, M., Shen, L., & Li, Y. (2021). Analysis on the Adaptability of Higher Vocational Colleges' Professional Settings and Industrial Structure under the Background of "Double-Higher"—Taking Jiangsu Agricultural-related Higher Vocational Colleges as an Example. Chinese Vocational and Technical Education, (20), 47–51. https://doi.org/CNKI:SUN:ZONE.0.2021-20-008

Yu, Z., & Yu, J. (2023). Evaluation of the coordinated development between Chinese cultural industry and scientific & technological innovation. PLOS ONE, 18(7), e0284213. https://doi.org/10.1371/journal.pone.0284213

Zhan, Q., Li, G., & Zhan, W. (2023). Measurement of the coupling coordination relationship between the structures of secondary vocational school programs and industries in China. Humanities and Social Sciences Communications, 10(1). https://doi.org/10.1057/s41599-023-01834-4

Zhang, Y., Hong, X., & Wang, Y. (2023). Study on the Coupled and Coordinated Development and Evolution of Digital Economy and Green Technology Innovation. Sustainability, 15(10), 8063. https://doi.org/10.3390/su15108063