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Temporal and Spatial Evolution of Coupling Coordination Degree of Industrial Innovation Ecosystem—From the Perspective of Green Transformation

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Abstract: This paper takes the industrial innovation ecosystem as the research object and the realization of green development as the goal, discussing the temporal and spatial evolution of coupling coordination degree of industrial innovation ecosystem from the perspective of system view. Based on the data of 30 provinces in China from 2010 to 2021, the spatial and temporal pattern distribution and spatial connection evolution of synergy among the three subsystems of industrial innovation ecosystem are studied by using coupling coordination degree model, trend surface model and gravity model. It is found that during the study period, the coupling relationship between the three subsystems is in a dynamic upward state. The regions with high values and rapid growth are distributed in the key areas of the national economic development strategy. At the same time, they have the characteristics of "positive U-shaped first and then inverted U-shaped" in the east-west and north-south directions; the spatial connection strength of coupling coordination degree shows that the spatial connection strength of the eastern region is significantly greater than that of the western region. With the improvement of spatial connection strength, a radial coupling network centered on Beijing Tianjin Tangshan region and the Yangtze River Delta is formed, which is of core significance to promote the coordinated development of industrial innovation ecosystem.

Keywords: industrial innovation ecosystem; green transformation; coupled co scheduling; temporal and spatial distribution

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1. Introduction

The 14th Five-Year Plan for National Economic and Social Development of the People's Republic of China and the Outline of Long-Term Goals for 2035 pointed out that it's important to promote the harmonious coexistence between people and nature and accelerate the green transformation, ensuring the coordinated promotion of high-quality economic development and high-level protection of the ecological environment. Green transformation refers to taking the construction of ecological civilization as the leading, circular economy as the foundation and green management as the guarantee. Its core content is the transformation from traditional development mode to scientific development mode. Concurrently, high quality economic development must depend on scientific and technological innovation system, and the high level of ecological environment protection means that it is very important to implement the ecological environment strategy combined with innovative technology. As the concept of green transformation and innovation ecosystem has been paid more attention at the macro level [1–3], the innovation ecosystem combining green transformation and technological innovation will be more in line with the goal of "peak carbon dioxide emissions and carbon neutralization" and the driving force of growth changes from factor driven to innovation driven. Further, high-tech industry is at the core of national development because of its unique innovation ability and complete management system. Then, under the background of green transformation, the research on the innovation ecosystem of high-tech industry has become a meaningful proposition.

The circulation of capital, talents, and technology in the industrial innovation ecosystem provides necessary support for innovation activities and processes. There is a value relationship among innovation subjects, consumers, government, and society in the industrial innovation ecosystem. Innovation subjects are the producers of innovative knowledge and technology, the industry is the main body of this system, consumer behavior plays a guiding role, and the environmental factor composed of government and society has a supporting effect [4]. Each subject is interdependent with the innovation ecological environment, creating more value for industrial stakeholders. Therefore, just as the stability of the ecosystem in the ecosystem is inseparable from the normal interaction between species, the harmony and stability of the industrial innovation ecosystem are inseparable from the good development of the collaborative relationship between elements and subjects [5,6]. The relevant coupling and coordination relationship directly determines the overall performance of the industrial innovation ecosystem. However, there are still problems of uneven levels of scientific and technological innovation, patchwork of innovation elements and low utilization of innovation resources [7]. In some regions, due to the one-sided emphasis on the input of single elements, the "fragmentation" and "isolation" of innovation and the imperfect innovation system, the original innovation ability is insufficient, the transformation ability of scientific and technological achievements is limited. The phenomenon that innovation vitality does not increase but decreases seriously restricts the healthy and sustainable development of innovation ecosystem. Therefore, it's important to research on the coupling and synergy existing in the industrial innovation ecosystem for finding the gap between regions, so as to narrow the regional differences and promote the coordinated development of economy.

This paper takes the industrial innovation ecosystem as the research object and the realization of green development as the goal. Based on the analysis of its connotation, structure, and characteristics, this paper discusses the internal mechanism and development power of the industrial innovation ecosystem from the perspective of system view, so as to provide an important reference for the industry to improve its innovation ability and adapt to the high-quality development of China at the present stage. The innovative points lie in the following aspects. Firstly, taking the industrial innovation ecosystem as the research object and achieving green development as the goal, this paper makes a black box deconstruction of the industrial innovation ecosystem. Secondly, based on the analysis of its connotation, structure, and characteristics, this paper discusses the internal mechanism and development power of the industrial innovation ecosystem from the perspective of system view. Finally, this paper breaks through the spatial limitations and forms pioneering research on evolution, makes up for the gap in the evolution of the spatial pattern of coupling coordination degree and provides an important reference for the industry to improve its innovation ability, adapting to China's high-quality development at the present stage.

2. Literature Review

With the development of the innovation paradigm and management concept, innovation theory has evolved from "national innovation system" [8] to "innovation ecosystem" [9,10]. Since then, relevant scholars have extended the concept of ecosystem to "industrial innovation ecosystem" [11,12] and "regional innovation ecosystem" [13,14] and carried out new research on innovation ecosystem to lay a foundation for the research of industrial ecosystem. On the one hand, based on the ecological theory, using the method of analogy and metaphor, combined with the practical development, the innovation ecosystem was newly interpreted [15]. The evaluation index system of innovation ecosystem is constructed to discuss the relationship among the four subsystems of operation, R&D, support and environment in the innovation ecosystem from the dynamic perspective of innovation activities [16]. On the other hand, relevant scholars have studied the internal synergy of innovation ecosystem, and the relevant research focuses on the impact of the synergy between innovation elements on the development and innovation performance of innovation ecosystem: Innovation subject [17–19], innovation subject and innovation environment [20,21] would promote the formation of network structure of innovation ecosystem through collaborative evolution, symbiosis and cooperation; The allocation of talents would weaken the collaborative process between the innovation subject and the innovation environment, symbiosis and coordination with the innovation ecosystem, and improve the system structure and function [22]. Recently, the synergy among the elements of innovation subject, innovation resources and innovation environment [23], the collaborative transformation of knowledge innovation and technology and the excellent spatial operation of the collaborative transformation field [24,25] will improve the transformation of innovation technology standards and positively drive innovation performance.

On the research method of synergy, Ariken Muhadaisi [26] used multi-source remote sensing data to comprehensively evaluate the coupling and coordination relationship between urbanization and ecological environment with a coupling coordination degree model. An empirical study on the coupling effect of the enterprise innovation system was carried out, with management innovation and technological innovation as the main research objects, the system coupling degree between them as the explanatory variable, and the innovation efficiency of enterprises as the explained variable [27]. López-Nicolás [28] measured the coordination degree of regional high-quality economic development and scientific and technological innovation by using the coupling coordination degree model and found that the two regions have evolved into coordinated development; Lengyel [29] calculated coordination to test the synergy of innovation environment, innovation input, and innovation output in the regional innovation system and found that the overall development trend of China's innovation capability was well, and the coordination of innovation environment and innovation input, innovation environment, and innovation output showed a gradient change trend in space.

To sum up, the existing research focuses on the exploration of the industrial innovation ecosystem. Based on the perspective of green transformation, the construction of industrial green innovation ecosystem is in a "black box" state. Next, most of the current researches on the internal synergy of innovation ecosystem focus on the collaborative evolution of innovation elements, and few study the coupling mechanism of industrial innovation ecosystem from the perspective of system view. Thirdly, although the coupling coordination degree is a commonly used method to study the coupling synergy, there are few literatures on the spatio-temporal pattern evolution of the coupling coordination relationship. Thus, the main research contents of this paper are as follows: (1) based on the frontier perspective of green transformation, this paper deconstructs the "black box" of industrial green innovation ecosystem; (2) based on the dynamic process of industrial innovation, this paper divides the industrial innovation ecosystem into three subsystems; (3) this paper constructs a multi-dimensional index system that can comprehensively reflect the level of regional industrial innovation activities, which lays a foundation for the normative judgment of the degree of mutual promotion or restriction of subsystem functions; (4) breaking the traditional thought focusing on the collaborative evolution of innovation elements, this paper studies the coupling mechanism of industrial innovation ecosystem from the perspective of system view; (5) breaking through the spatial limitations, this paper studies the spatial-temporal pattern distribution and spatial connection evolution of the synergy between the three subsystems.

3. Theoretical Model of Industrial Innovation Ecosystem

Innovation has the characteristics of high complexity, high cost, high risk and long cycle [30,31], which requires cooperative innovation by multiple innovation subjects [32]; Innovation ecosystem is mainly characterized by ecology, dynamics and openness [33]. At this stage, the connotation of industrial innovation ecosystem adds the relevant concepts of green development. Therefore, it is concluded that industrial innovation ecosystem has the characteristics of green development, diversity, dynamics, ecology, sustainability, and risk. Based on the industrial innovation dynamic perspective of innovative knowledge output, innovative technology output and technological business value transformation, combined with the characteristics of industrial innovation ecosystem, this paper constructs knowledge subsystem, innovation subsystem, and industrial subsystem. Through interaction, integration, and intersection, the three systems form an innovation ecosystem of high-tech industry [34]. Papers and topics are the main carriers carrying knowledge genes [35], and inject vitality into the knowledge subsystem through the collaborative interaction of relevant subjects and elements. Patents and scientific research projects are typical representative achievements of innovative technologies. Under the joint influence of talents, funds, commercial marketplace and economic environment, patents and scientific research projects provide innovation power for the innovation subsystem and lay a foundation for the innovation commercialization in future industries development. The industrial subsystem with high-tech enterprises and service institutions as the main body is committed to green transformation and produces economic, environmental, and social benefits at the same time.

3.1. Knowledge Subsystem

Knowledge is the foundation of all innovation activities, and knowledge subsystem is the basis of industrial innovation ecosystem. In the process of industrial innovation, we obtain knowledge reserves from universities and R&D institutions and absorb excellent innovative talents from knowledge subjects.

The most important constituent element of the knowledge subsystem is knowledge. Innovative talents take the innovation subject as the knowledge carrier and the internal and external innovation funds as the R&D investment [36] and complete the knowledge output in four stages: Firstly, using the existing knowledge reserve to extract valuable information through various channels and complete the knowledge absorption [37]; secondly, recombining relevant knowledge factors and knowledge associations in structure to realize knowledge integration; and thirdly, based on the carrier of knowledge innovation, sharing their own cutting-edge theories to realize the cross organizational flow of knowledge. Finally, through knowledge sharing, integrating advantageous resources and complete knowledge innovation, and in the future, it will be combined repeatedly according to practical requirements to realize the renewal and evolution of knowledge [38]. At the same time, in the process of knowledge output, the government provides R&D funding support for colleges and universities and R&D institutions, solving the financial difficulties through effective cooperation between industry, University, and research, and producing economic and social benefits.

3.2. Innovation Subsystem

Under the background of green transformation, the key of innovation subsystem in industrial ecosystem lies in technology. In order to achieve high-quality development, innovative technology should be endowed with green attribute. The technology should be put into production according to the minimum ecological negative effect [39,40] to produce green products with pollution-free green process, green recycling equipment, and green product design [41].

Knowledge innovation ultimately serves to solve practical problems, and technological innovation is an important part in the application of knowledge. Technological innovation cannot be completed only by the innovation subject itself, but by the joint efforts of Technology exchange, market orientation, government support, and environmental impact. First, the basic technology, cutting-edge technology and common technology required by the innovation subject to carry out innovation activities are the basis of technological innovation. It is important for promoting the project and upgrades the products to widely absorb internal and external excellent scientific and technological achievements and patented inventions, and fully communicate with the external technology market [42]. Next, the purchasing power of consumers in the innovative market and the trading results of technology transformation products market have market guidance for the transformation of green technology, and the main body of technology transformation optimizes the technology through the test and feedback of the market. Besides, the government's financial support to the innovation subject will reduce the cost of technological innovation and R&D risk, creating innovation motivation and improving innovation efficiency [43]. Also, social, and economic resources are naturally accumulated and full of productivity, which can help enterprises to realize their objectives.

3.3. Industrial Subsystem

Innovation ultimately serves to solve practical problems and turns into practical value, which is to transfer innovation output from one organization to another and create economic benefits through commercialization [44]. In the process of technology transformation, high-tech enterprises with commercial value will become the main subject of technology transformation. At the same time, with the continuous emergence of start-ups and small and medium-sized science and technology enterprises, government and society gradually pay more attention to the construction of service organization platforms such as science and technology incubators, provide information resources and professional services, and provide strong support for the cultivation and construction of industrial innovation ecosystem.

The industrial development under green transformation should be guided by the concept of green development, based on the current economic and social development and the bearing capacity of resources and environment, and realize enterprise green operation, efficient utilization of resources and government green supervision by changing the operation mode, resource consumption structure and government supervision means of high-tech enterprises. And in the current environment of green transformation, a good natural ecological environment is the basis for the normal operation of the industrial ecological innovation system [45]. For example, water resources are essential resources in the development of green ecology. Simultaneously, as the largest carbon pool in the terrestrial ecosystem, forest carbon is gradually becoming an important tool for many countries to solve the problem of climate change and is committed to reducing the concentration of greenhouse gases and slowing down the process of climate warming. Furthermore, low carbon economy aims at sustainable development and reducing carbon emissions, relying on technological innovation and clean energy development such as electric energy. For example, through the development and application of environmental protection technology, carbon (c) and sulfur (s) emissions in industrial production can be reduced and the "three wastes" of traditional industry comprehensive utilization rate can be increased, which can lead to realize the treatment and recycling of pollutants discharged from non-clean energy such as coal, oil and natural gas, achieve the low-carbon development of energy flow and the recycling of resource flow, reduce the consumption of high-carbon energy and carbon dioxide emission as much as possible, so as to solve the problem of climate warming and realize the synchronous development of economic development and ecological protection [46,47].

4. Construction of Comprehensive Index System of Industrial Innovation Ecosystem

4.1. Construction of Comprehensive Evaluation Index System

Based on the above theoretical analysis, an innovation ecosystem evaluation index system with 19 primary indicators and 43 secondary indicators is constructed. The comprehensive evaluation system of knowledge subsystem includes 5 aspects and 10 secondary indexes related to knowledge, such as subject, talent, and capital, which describes the knowledge production potential of knowledge subsystem. The comprehensive evaluation system of innovation subsystem includes innovation subjects such as universities, R&D institutions and industrial enterprises above designated size, as well as 16 indicators in 7 aspects such as market guidance and government support to describe the innovation ability of innovation subsystem. The comprehensive evaluation system of industrial subsystem is composed of 17 indicators from 7 aspects, such as high-tech enterprises, service institutions, technology transformation capacity, and government environmental regulation, reflecting the driving effect of self-development and external policies on industrial innovation operation. Compared with previous studies, this paper changes the establishment of subsystem indicators based on innovation factors and internal and external factors [48,49]. This paper integrates the above factors into each system to establish an indicator system. At the same time, it adds indicators related to green development such as pollutant emission and treatment. The establishment of comprehensive evaluation index system of industrial innovation ecosystem is shown in Table 1. The relevant data is shown in the Supplementary Materials, Table S1: Data.

Table 1. Comprehensive Evaluation Index System of Industrial Innovation Ecosystem.

Subsystem	Primary Index	Secondary Index
Knowledge subsystem	Knowledge reserve	Number of published scientific papers Number of published scientific and technological works
	Knowledge subject	Number of colleges and universities Number of R&D institutions
	Intellectual talents	Full time equivalent of R&D project investment personnel in Colleges and Universities Full time equivalent of R&D project input personnel of research and development institutions
	Knowledge funds	Internal expenditure of R&D project investment in Colleges and Universities Internal expenditure of R&D project investment funds of research and development institutions
	Knowledge cooperation	Amount of R&D funds of colleges and universities from enterprises Amount of R&D funds of R&D institutions from enterprises
Innovation subsystem	Innovative achievements	Number of invention patents authorized Number of R&D projects
	Innovation ability	Number of valid patents of colleges and universities/Number of colleges and Universities Number of valid patents of R&D institutions/Number of R&D institutions
	Innovation funds	Number of valid patents of enterprises/number of industrial enterprises above designated size with R&D activities Internal expenditure of R&D funds in Colleges and Universities Internal expenditure of R&D funds of research and development institutions Internal expenditure of R&D funds of industrial enterprises above designated size
	Trading market	Turnover of export technology market Turnover of absorbing technology market
	Technical exchange	Number of foreign technology import contracts
	Government support	Government investment in Colleges and Universities Government investment in R&D institutions Government investment of industrial enterprises above designated size
	Economic environment	Per capita GDP Per capita consumption expenditure

Table 1. *Cont.*

Subsystem	Primary Index	Secondary Index
Industrial subsystem	Industrial Subject	Number of high-tech enterprises
	Service organization	Number of technology business incubators
		Number of science and Technology Museums
	Achievement transformation	Total output value of high-tech industry/number of R&D institutions
		New product sales revenue
	Ecological environment	Water resource
		Urban greening coverage
		Forest coverage
	Low carbon development	Coal consumption/total energy consumption
		Oil consumption/total energy consumption
		Natural gas consumption/total energy consumption
		Carbon emissions
	Circular development	Generating capacity
		Waste water consumption
		Comprehensive utilization of general industrial solid waste
	Pollutant treatment	Completed investment of government pollution control project
		Wastewater treatment/wastewater discharge
		Waste gas treatment/sulfur dioxide emission
		Solid waste treatment/solid waste discharge

4.2. Data Source and Processing

The 12-year data of 30 provinces (autonomous regions and municipalities directly under the central government) from 2010 to 2021 are selected as the research object. All the data are from China Statistical Yearbook, China Science and Technology Statistical Yearbook and China Torch Statistical Yearbook over the years. To solve the large gap caused by the inconsistency of index dimensions, this paper uses non-negative dimensionless data processing. At the same time, using the normalization method to form standardize the positive and negative indicators.

$$r_{ij} = \begin{cases} \frac{(X_{ij}-X_{\min})}{(X_{\max}-X_{\min})} + 0.1 \\ \frac{(X_{\max}-X_{ij})}{(X_{\max}-X_{\min})} + 0.1 \end{cases} \tag{1}$$

5. Temporal and Spatial Pattern of Coupling Coordination Degree of Industrial Innovation Ecosystem

5.1. Comprehensive Evaluation Level of Subsystem

As a tool widely used to determine the weight of various indicators, information entropy can better provide basis for multi-index comprehensive evaluation [50]. In this paper, the entropy weighting method is used to calculate the entropy weight of each index. The calculation process is as follows:

$$h_{ij} = \frac{r_{ij}}{\sum_{i=1}^{n} r_{ij}} \tag{2}$$

$$h_j = -k\sum_{i=1}^{n} h_{ij} \ln \ln h_{ij} \; (In\ the\ formula, k = \frac{1}{\ln n}) \tag{3}$$

$$d_j = 1 - h_j \tag{4}$$

$$\lambda_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{5}$$

h_{ij}, h_j, d_j and λ_j respectively represent the proportion, entropy value, difference coefficient and entropy weight of the evaluation index j in the system i. The greater the entropy weight, the more important it is in the comprehensive evaluation.

According to the steps of entropy weighting method, the weight of each index can be obtained for the calculation of coupling coordination degree.

5.2. Measurement of Coupling Coordination Degree

Under the influence of internal and external factors, the coupling degree can reflect the synchronization degree of the evolution of multiple subsystems. In this paper, the coupling degree model will be used to measure the coupling relationship among the three subsystems of knowledge subsystem, innovation subsystem and industry subsystem [51], and the calculation formula is shown in Equation (6).

$$C = \frac{\sqrt[3]{U1U2U3}}{U1U2U3/3} \tag{6}$$

Among them, $U1$, $U2$ and $U3$ respectively represent the comprehensive evaluation indexes of knowledge subsystem, innovation subsystem and industry subsystem of this study;C represents the coupling degree between the three subsystems. The greater its value, the higher the correlation between the systems.

Furthermore, the degree of coupling can only reflect the synchronization of evolution between systems and cannot reflect the development level of the three subsystems. However, based on the comprehensive development level of each system, the coupling coordination degree can better judge the benign effect degree between systems, explore the integration level between systems, and provide suggestions for further in-depth integration and reaching extreme coordination [52]. Therefore, based on the coupling degree model, this paper will further use the coupling coordination degree model to measure the coupling relationship, and the calculation formula is shown in Equation (7).

$$D = \sqrt{CT} = \sqrt{C(\alpha U1 + \beta U2 + rU3)} \tag{7}$$

D represents the coupling co scheduling of three systems in the region; T represents the composite index of the three; α, β and γ are the weights of comprehensive evaluation indexes of knowledge subsystem, innovation subsystem and industrial subsystem respectively, and $\alpha + \beta + \gamma = 1$, $\alpha = \beta = \gamma = 1/3$. According to the existing references, this paper establishes the evaluation criteria for the coupling coordination degree [53], as shown in Table 2.

Table 2. Evaluation Criteria of Coupling Coordination Degree.

Serial Number	Type	Grade	Numerical Value
1	Maladjusted Stage	Extreme Disorder	$0 \leq D < 0.1$
2		Severe Disorder	$0.1 \leq D < 0.2$
3	Antagonistic Stage	Moderate Disorder	$0.2 \leq D < 0.3$
4		Mild Disorder	$0.3 \leq D < 0.4$
5		Verge of Disorder	$0.4 \leq D < 0.5$
6	Grinding-in Stage	Reluctantly Coordinate	$0.5 \leq D < 0.6$
7		Primary Coordination	$0.6 \leq D < 0.7$
8		Intermediate Coordination	$0.7 \leq D < 0.8$
9	Coupling Stage	Good Coordination	$0.8 \leq D < 0.9$
10		Highly Coordination	$0.9 \leq D \leq 1$

5.3. Spatiotemporal Distribution Characteristics of Coupling Coordination Degree

According to the measurement of the above system comprehensive evaluation index and the calculation of coupling coordination degree, the coupling coordination dispatching of three systems in 30 provinces in China from 2010 to 2021 is obtained. To further show their change trend and spatial distribution, radar charts and broken line charts are drawn, as shown in Figures 1 and 2. (The data about Coupling Coordination Degree is shown in the Supplementary Materials, Table S1: Data).

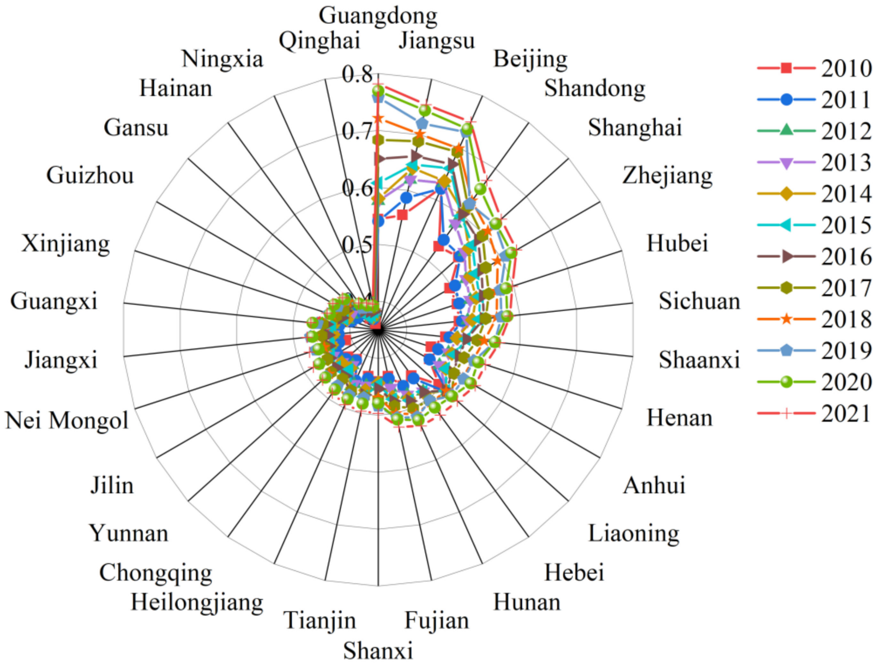


Figure 1. Radar Chart of Coupling Coordination Degree of "Knowledge Subsystem-Innovation Subsystem-Industry Subsystem" from 2010 to 2021.

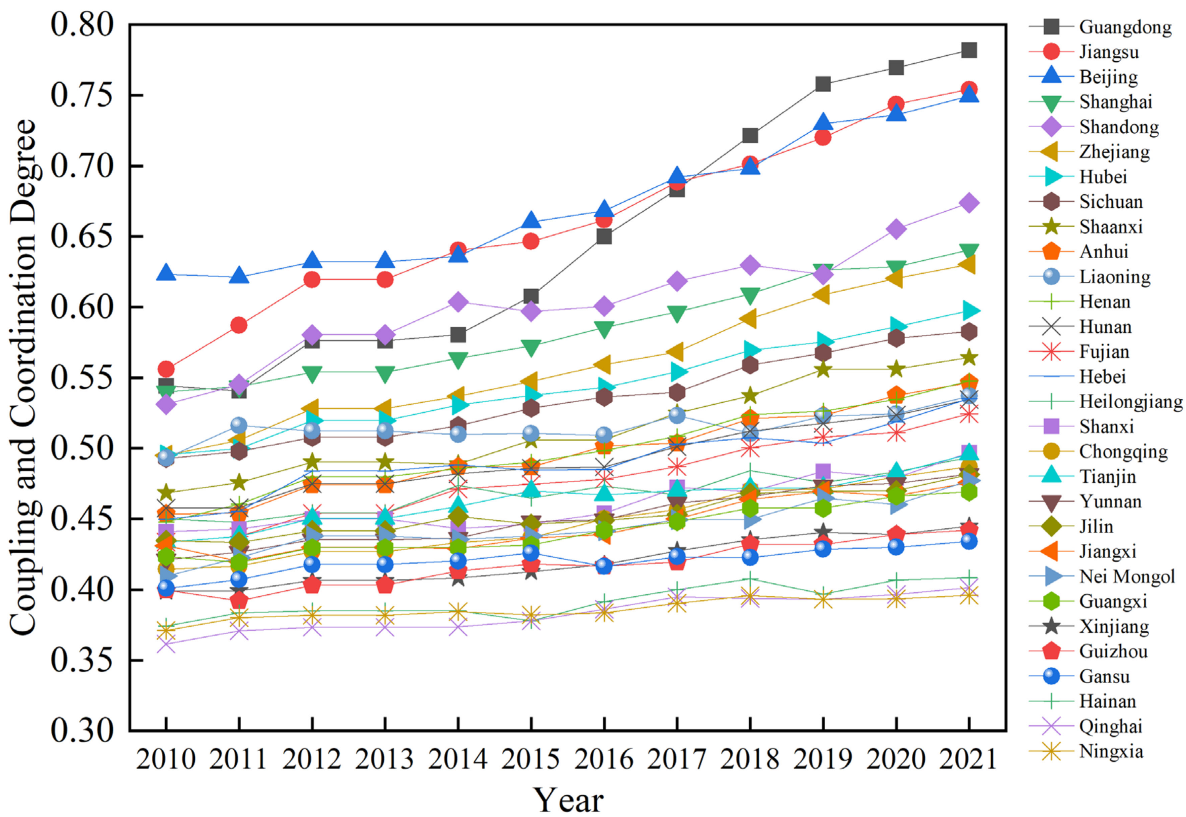


Figure 2. Broken Line Diagram of Coupling Coordination Degree of "Knowledge Subsystem-Innovation Subsystem-Industry Subsystem" from 2010 to 2021.

It can be seen from Table 3, Figures 1 and 2 that Guangdong, Jiangsu, Beijing, Shandong and Shanghai were in the grinding-in stage, Zhejiang, Hubei, Sichuan, Shaanxi, Henan, Anhui, Liaoning, Hebei, Hunan and Fujian were in the grinding-in stage from the antagonistic stage, and Shanxi, Tianjin, Heilongjiang, Chongqing, Yunnan, Jilin, Inner Mongolia, Jiangxi, Guangxi, Xinjiang, Guizhou, Gansu, Hainan, Ningxia and Hainan were in the antagonistic stage from 2010 to 2021. From the perspective of time, although the coupling coordination degree of each province in China does not increase year by year, it shows an upward coordination trend. From the perspective of space, the coupling and coordination degree in each province is not balanced. The regions with high coupling degree and rapid growth rate are distributed in the Bohai Economic Circle, Jiangsu Coastal Economic Zone, Yangtze River Delta Economic Zone, and Guanzhong Tianshui Economic Zone, which are consistent with the key areas of the national economic development strategy.

5.4. Trend Surface Analysis of Coupling Coordination Degree

Since charts and broken line charts only express the change trend of numerical values and cannot intuitively show the spatial regional relationship of coupling coordination scheduling, this paper will utilize the trend surface analysis method to visually analyze the spatial distribution of coupling coordination degree through three dimensions [54]. The specific practice is as follows: projecting the coupling coordination degree onto the x-z plane and y-z plane to form a fitting curve with Matlab, which can reflect the trend of coupling coordination in all directions. In this paper, the cubic polynomial curve fitting method is adopted because of its high fitting accuracy. The relevant calculation formula is as follows:

$$\rho(x) = \rho_1 x^3 + \rho_2 x^2 + \rho_3 x + \rho_4 \tag{8}$$

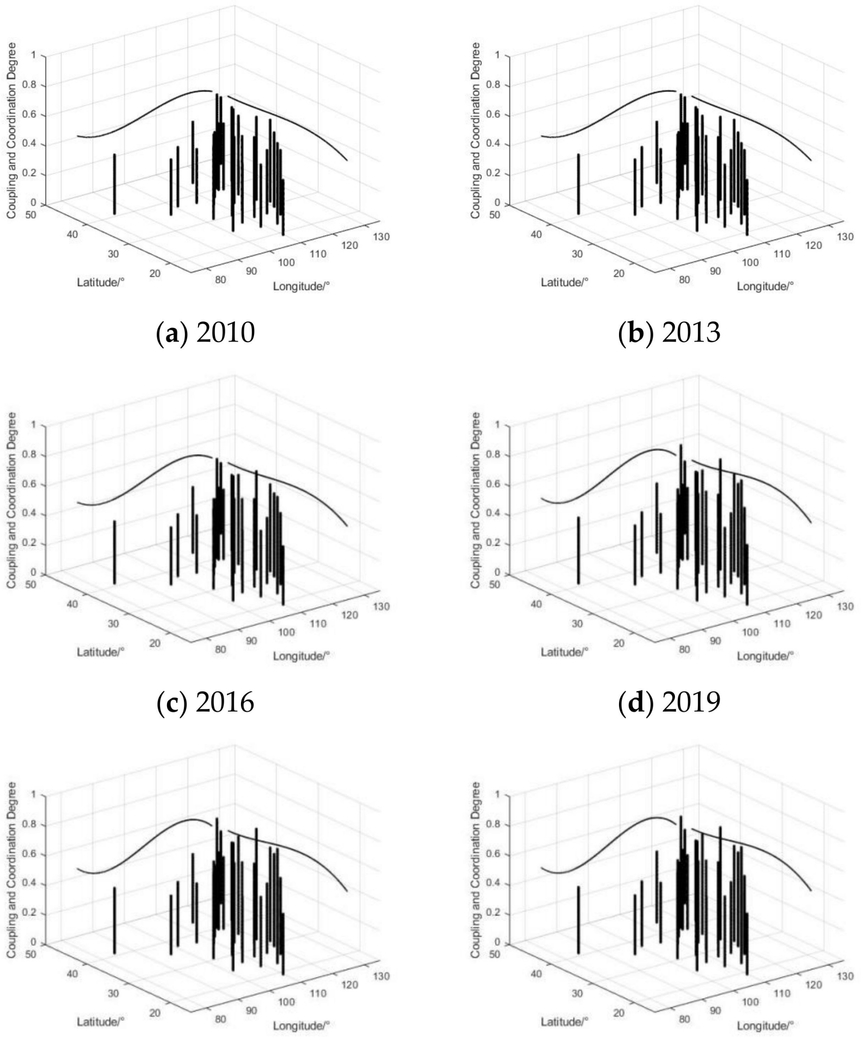
$$q(y) = q_1 y^3 + q_2 y^2 + q_3 y + q_4 \tag{9}$$

Inside,$\rho(x)$ and $q(y)$ are the fitting values of the coupling coordination degree calculated in the longitude and latitude directions through the above formula. X-axis represents longitude, y-axis represents latitude, z-axis represents coupling coordination. In addition, ρ and q represent the polynomial coefficients.

Through the above calculations, Figure 3 is obtained, which shows the trend of changes in the coupling and coordination degree of the “knowledge subsystem-innovation subsystem-industrial subsystem” in the six years of 2010, 2013, 2016, 2019, 2020 and 2021.

From 2010 to 2021, the degree of coupling coordination in China maintained a spatial distribution of “high in southeast and low in northwest”: the projection trend lines of the x-z plane (indicating the east-west direction) and y-z plane (indicating the north-south direction) both showed the characteristics of “U-shape first, U-shape backward”. The degree of coupling coordination in the west-central and north-central regions changes from a downward state to an upward state, which is a turning point, indicating that the coupling coordination degree in the northwestern region is the lowest. On the contrary, the “U-shaped” highest point appears in the east-central and south-central regions, indicating the highest degree of coupling and coordination in the southeast.

The “U-shape” formed on the x-z plane is deeper than the “U-shape” formed on the y-z plane, showing that the spatial distribution difference of the three systems in the east-west direction is greater than that in the north-south direction. As time goes on, the deepening of the “U-shape” displayed on the x-z and y-z projections indicates that the difference in the degree of coupling and coordination of the provinces across the country in the east-west and north-south directions has gradually increased during the study period. In summary, the region that contains a higher level of knowledge subsystem, innovation subsystem and industrial subsystem’s coupling and coordinated development is the southeast region. It’s a typical region where the system is evolving in an orderly manner, and it will also be the backbone of narrowing the gap between regions.



(**a**) 2010 (**b**) 2013

(**c**) 2016 (**d**) 2019

(**e**) 2017 (**f**) 2019

Figure 3. The Trend Surface Change Diagram of the Coupling Coordination Degree of "Knowledge Subsystem-Innovation Subsystem-Industrial Subsystem".

6. Spatial Connection of Coupling and Coordination Degree of Industrial Innovation Ecological Subsystem

6.1. Gravity Model

The spatial connection of the coupling coordination degree of the industrial innovation ecological subsystem refers to the spatial interaction formed between the coupling coordination degree of the knowledge subsystem, the innovation subsystem, and the industrial subsystem. Hua Xiangyu et al. [55] believed that the gravity model is one of the effective models for measuring the above-mentioned spatial interactions. Therefore, the establishment of a gravity model is shown in Equation (8).

$$R_{ij} = K\frac{D_i D_j}{G_{ij}^2} \quad (10)$$

Among them, Rij represents the spatial connection strength between the three-systems coupling coordination degree of province i and province j. The larger the value, the greater the spatial connection strength; K represents the gravitational constant with a value of 1; Di and Dj represent the province i and the degree of coupling coordination of the province j; G_{ij}^2 represents the spatial distance between province i and province j.

According to Equation (8), Arcgis is used to calculate the spatial connection strength of the coupling and coordination of the knowledge subsystem, innovation subsystem and industrial subsystem among 30 provinces in the country in 2010, 2013, 2016, 2019, 2020 and 2021, and draw the gravitational diagram of the degree of coupling and coordination of the provincial inter-regional system with Matlab, which is shown in Figure 4:

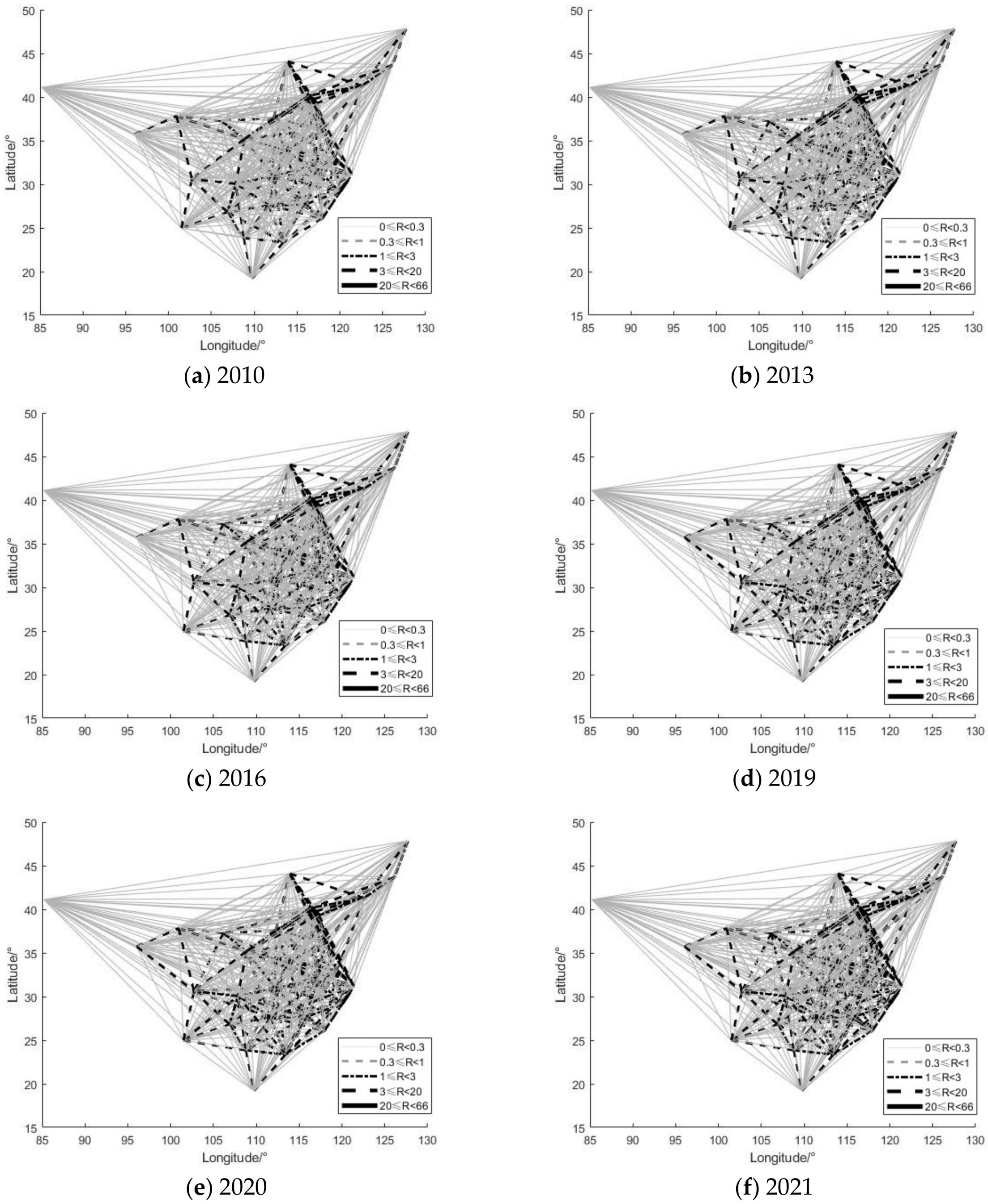


Figure 4. The Gravity Diagram of the Coupling and Coordination Degree of "Knowledge Subsystem-Innovation Subsystem-Industry Subsystem".

Through Figure 4, we can intuitively discover the spatiotemporal evolution of the spatial gravity between regions in the process of coupling and coordination of the industrial innovation ecosystem. From a spatial point of view, the regional distribution of spatial linkage strength is uneven. The spatial linkage strength in the eastern region is significantly greater than that in the western region. During the study period, the spatial linkage between the Beijing-Tianjin-Tangshan region and the Yangtze River Delta has maintained a relatively high intensity. At the same time, with the above-mentioned regions as the center, the spatial connection intensity decreases to the surroundings; from the perspective of time, with the passage of time, the spatial connection intensity of the coupling and coordination of the three subsystems of the knowledge subsystem, the innovation subsystem, and the industrial subsystem continues to increase as a whole. The azimuth trend of increasing intensity is from the east coast to the northwest. The above conclusions continue to verify the previous conclusions.

6.2. Space Potential Energy Value

Based on the gravity model, the spatial connection strength between systems R_i can be measured, that is, the sum of the spatial connection strength between the city i and other provinces, as the potential energy value of the spatial connection of the coupling coordination degree studied in this paper, as shown in Equation (9) Show.

$$R_i = \sum_{j=1}^{n} R_{ij} \tag{11}$$

According to Equation (9), the potential energy values of the coupling coordination degree of 30 provinces across the country in 2010, 2013, 2016, 2019, 2020 and 2021 are measured and calculated, and the results are shown in Table 3. The larger the spatial potential energy value corresponding to each region, the higher the central position that can describe the spatial connection between the province and other provinces, and the stronger the radiation drive to the region [25,38].

It can be seen from Table 3 that the spatial potential energy values of provinces increased, proving that the coupling coordination degree of the three subsystems increases and the spatial relationship is closer, which is consistent with the above conclusions. From a spatial perspective, the spatial connection potential energy value of Beijing-Tianjin-Tangshan region where Beijing, Tianjin and Hebei are located and the Yangtze River Delta area where Shanghai, Jiangsu and Zhejiang are located account for the largest proportion in China. With the passage of time, the status of the above areas has not changed significantly, and the potential energy value of the surrounding areas has gradually increased.

Combined with the conclusion of the gravity model, it can be found that the spatial connection of the coupling coordination degree forms a radial network centered on the two regions to the surrounding: The first center is Beijing-Tianjin-Tang region, and diffuses radially to regions with similar geographical locations such as Hebei, Henan, Shandong and Shaanxi; the second core is to take the Yangtze River Delta as the center and spread to the middle and lower reaches of the Yangtze River, Jiangsu Coastal Economic Zone, Chengdu Chongqing Economic Zone and the Economic Zone on the West Bank of the Strait. The reason why Beijing Tianjin Tangshan region and the Yangtze River Delta region can become the center is that the two regions have rapid economic development, advanced infrastructure, adjacent location, and high concentration of core elements, which will quickly produce spatial spillover effect in the block region and promote regional development; At the same time, the two core areas' high-level economic development has a driving effect on the surrounding areas. With the decrease of distance, the driving effect is stronger, so as to form a radiation network. To sum up, the above two core regions promote the coordinated development between regions and play a central role in promoting the spatial coupling between knowledge subsystem, innovation subsystem and industrial subsystem.

Table 3. Spatial Connection Potential Energy and Proportion of Each Region.

Year	2010	2013	2016	2019	2020	2021	2010	2013	2017	2019	2020	2021
Region	**Spatial Potential Energy**						**Proportion**					
Beijing	75.792	81.786	87.652	99.006	102.429	107.373	18.053%	17.826%	17.765%	17.931%	17.937%	18.009%
Tianjin	43.412	47.178	50.391	54.183	56.441	59.406	10.273%	10.167%	9.567%	9.457%	9.851%	10.369%
Hebei	72.529	79.943	84.064	93.357	97.317	102.476	17.163%	17.228%	15.961%	16.295%	16.986%	17.887%
Shanxi	11.235	12.045	12.580	14.171	14.264	15.115	2.659%	2.596%	2.388%	2.473%	2.490%	2.638%
Nei Mongol	5.043	5.610	5.843	6.488	6.513	6.905	1.193%	1.209%	1.109%	1.132%	1.137%	1.205%
Liaoning	7.722	8.354	8.587	9.273	9.440	9.892	1.827%	1.800%	1.630%	1.619%	1.648%	1.727%
Jilin	4.850	5.117	5.335	5.797	5.875	6.154	1.148%	1.103%	1.013%	1.012%	1.025%	1.074%
Heilongjiang	2.819	2.950	3.150	3.328	3.411	3.564	0.667%	0.636%	0.598%	0.581%	0.595%	0.622%
Shanghai	14.923	16.374	18.242	20.939	21.484	22.279	3.531%	3.529%	3.464%	3.655%	3.750%	3.889%
Jiangsu	18.257	21.276	23.795	27.375	28.785	29.784	4.320%	4.585%	4.518%	4.778%	5.024%	5.199%
Zhejiang	12.972	14.450	16.075	18.652	19.254	19.942	3.070%	3.114%	3.052%	3.256%	3.361%	3.481%
Anhui	15.266	16.997	18.866	21.079	22.083	22.875	3.612%	3.663%	3.582%	3.679%	3.854%	3.993%
Fujian	8.506	9.243	10.184	11.636	11.834	12.362	2.013%	1.992%	1.934%	2.031%	2.066%	2.158%
Jiangxi	10.771	11.268	12.095	13.841	13.949	14.511	2.549%	2.428%	2.296%	2.416%	2.435%	2.533%
Shandong	15.029	17.262	18.563	20.364	21.773	22.873	3.556%	3.720%	3.524%	3.555%	3.800%	3.992%
Henan	12.528	14.066	15.198	17.021	17.568	18.369	2.965%	3.031%	2.886%	2.971%	3.066%	3.206%
Hubei	12.715	13.934	15.155	17.046	17.607	18.296	3.009%	3.003%	2.877%	2.975%	3.073%	3.193%
Hunan	10.286	11.067	11.889	13.490	13.828	14.362	2.434%	2.385%	2.257%	2.355%	2.414%	2.507%
Guangdong	7.337	8.031	9.380	11.529	11.858	12.248	1.736%	1.731%	1.781%	2.012%	2.070%	2.138%
Guangxi	6.285	6.610	7.134	7.903	8.166	8.345	1.487%	1.424%	1.354%	1.379%	1.425%	1.457%
Hainan	2.779	2.966	3.177	3.462	3.599	3.671	0.658%	0.639%	0.603%	0.604%	0.628%	0.641%
Chongqing	8.475	9.059	9.924	11.011	11.357	11.719	2.006%	1.952%	1.884%	1.922%	1.982%	2.045%
Sichuan	5.789	6.184	6.765	7.546	7.776	7.964	1.370%	1.333%	1.284%	1.317%	1.357%	1.390%
Guizhou	7.082	7.397	7.973	8.749	9.016	9.221	1.676%	1.594%	1.514%	1.527%	1.574%	1.610%
Yunnan	3.306	3.529	3.794	4.216	4.294	4.414	0.782%	0.760%	0.720%	0.736%	0.749%	0.770%
Shaanxi	10.128	11.043	11.793	13.605	13.780	14.269	2.397%	2.380%	2.239%	2.375%	2.405%	2.491%
Gansu	4.214	4.559	4.693	5.067	5.134	5.268	0.997%	0.982%	0.891%	0.884%	0.896%	0.920%
Qinghai	2.506	2.679	2.770	2.984	3.017	3.083	0.593%	0.577%	0.526%	0.521%	0.527%	0.538%
Ningxia	6.372	6.864	7.304	7.909	8.046	8.297	1.508%	1.479%	1.387%	1.381%	1.404%	1.448%
Xinjiang	0.911	0.966	1.023	1.133	1.142	1.176	0.216%	0.208%	0.194%	0.198%	0.199%	0.205%

7. Conclusions, Managerial Implications, and Research Limitations

7.1. Main Conclusions

Previous studies have concluded that the degree of coupling and coordination of innovation ecosystem is gradually increasing, and the level of coupling and coordination in coastal areas is higher than that in other areas [48]. Based on the above conclusions, this paper further studies the regions with strong spatial connection and the regions with core driving role, and obtains the conclusions. Specifically, this paper uses the coupling coordination degree model, trend surface model and gravity model to show the spatial-temporal pattern distribution and spatial connection evolution of the coupling effects among the three subsystems based on the data of 30 provinces and cities (excluding Hong Kong, Macao, Taiwan, and Tibet) from 2010 to 2021. The main findings and conclusions are as follows:

1. According to the results of the coupling coordination model, at the spatial level, the development of the coupling coordination degree of the knowledge subsystem, innovation subsystem and industrial subsystem in each province is uneven. The regions with high coupling degree and rapid growth rate are distributed in the Bohai Economic Circle, Jiangsu Coastal Economic Zone, Yangtze River Delta Economic Zone and Guanzhong-Tianshui Economic Zone, among which, Guangdong, Jiangsu, Beijing, Shandong and Shanghai remained in the grinding-in stage during the research period. In terms of time, from 2010 to 2021, the overall degree of coupling coordination showed an upward trend, and the system was developing towards benign coupling.

2. According to the results of the trend surface model, the projection trend lines of the coupling coordination degree in the east-west direction and the north-south direction of China show the characteristics of "positive U-shape first and then inverted U-shape". The highest point appears in the southeast region and the lowest point appears in the northwest region, indicating that the coupling and coordinated development level of the southeast region is higher, which is a typical region of systematic and orderly evolution. The formation of "U-shape" in the east-west direction is deeper than that in the north-south direction, indicating that the spatial distribution difference of the coupling coordination degree of the three systems in the east-west direction is greater than that in the north-south direction. At the same time, the "U-shape" in every direction is gradually deepening, showing that the problem of unbalanced development between regions has occurred in the coupling process of industrial innovation ecosystem.
3. According to the results of gravity model, the regional distribution of spatial connection strength is unbalanced, showing that the spatial connection strength of the eastern region is significantly greater than that of the western region. Among them, the spatial connection strength of Beijing-Tianjin-Tangshan region and the Yangtze River Delta is the highest. At the same time, with the passage of time, the spatial connection strength of coupling coordination degree is increasing, and the azimuth trend is from the east coast to the northwest.
4. According to the results of gravity model and spatial potential energy value, the total value of spatial connection potential energy in Beijing-Tianjin-Tangshan region where Beijing, Tianjin, and Hebei are located and the Yangtze River Delta where Shanghai, Jiangsu and Zhejiang are located account for the largest proportion in China. With the passage of time, the status of the above areas has not changed significantly. Simultaneously, it can be seen from the proportion of spatial potential energy value that it forms a radial diffusion around Beijing-Tianjin-Tangshan region and the Yangtze River Delta driving the spatial connection strength of the surrounding areas to strengthen over time, which also shows that the above two regions promote the coordinated development between regions and play a central role in promoting the spatial coupling between knowledge subsystem, innovation subsystem and industrial subsystem. It is of core significance to promote the coordinated development of industrial innovation ecosystem.

7.2. Managerial Implications

Through the research on the spatial-temporal coupling of knowledge subsystem, innovation subsystem and industry subsystem, it is found that although the coupling coordination level of the three subsystems has been improved, there is significant spatial heterogeneity and imbalance among regions. According to the current research status, this paper puts forward the following policy suggestions:

1. For regions with high coupling and coordination level, such as Beijing-Tianjin-Tangshan region and southeast coastal areas, we should continue to give full play to their advantages in innovative resources and economic development level, eliminate inefficient and high consumption industries, and reduce pollutant emissions. Meanwhile, we should make good use of the spatial driving role of regions with high coupling coordination degree and drive the coupling coordination degree of local and surrounding industrial subsystems with innovative knowledge and innovative technology to reach the coupling stage through the overflow of knowledge and technology driven by the flow of high-quality talents in these regions.
2. For the regions with medium coupling and coordination level in the central region, compared with the regions with high coordination level, the three systems are in the "Valley Area". We should make use of its geographical advantages, improve the level of opening up, rely on the middle and lower reaches of the Middle and Lower Yangtze River Economic Belt, carry out multi-directional regional cooperation, and

use external economic and innovative resources to drive its economic and innovative development. Internally, relevant policies and environmental regulation according to local characteristics should be formulated. Concurrently, the region is located at the intersection of east-west and north-south directions, and is the backbone to promote the balanced development of China's East, West, North, and South. We should strengthen the economic cooperation between relevant regions and provinces, forming a joint force for development to promote the development of regional integration.

3. For the areas with low coupling and coordination degree in the northwest, we should make full use of their advantages of high altitude and natural energy and develop clean energy such as wind and electric energy, reducing pollutant emissions from the source. Giving full play to resource advantages to drive regional development. Meanwhile, learning the innovation achievements of areas with high innovation level to advance local innovation development, and then promote the mutual coupling of the three systems, and narrow the gap gradually.
4. Strengthen the output of original technologies and promote disruptive innovation. Original new knowledge is the fundamental driving force to drive the emergence of new technologies, new products, and even new business models. At present, China's economic development is facing the problem of "neck sticking", because technological production does not echo the basic theory of the source. Further, China's innovation mode "Introduction Imitation" will always limit the thinking mode of innovators. On the contrary, we should consciously adhere to the original knowledge system to support innovation output, to achieve the subversive transcendence of innovative technology.
5. Enrich the main body of industrial innovation to promote high-quality industrial development. Heterogeneous subjects, whose functional eigenvalues have a large coefficient of variation, are an important factor in promoting the energy release of the innovation ecosystem, knowledge spillover and innovation development. To achieve independent innovation, China needs not only the support of multinational companies such as Huawei, but also the support of "invisible champions" small and medium-sized enterprises and small and micro "unicorn" enterprises. With their own advantages, these enterprises are of great significance to improve innovation efficiency. Therefore, enriching the main body of industrial innovation is an important content to improve the function of industrial innovation ecosystem.

7.3. Research Limitations

Firstly, this paper only studies the coupling relationship between subsystems of industrial innovation ecosystem, ignoring the linkage relationship of internal nodes of the system. Hence, in the later research, complex system theory can be used to study the relationship between nodes in the system and the symbiotic evolution between systems. Secondly, this paper studies the problems from the macro perspective. In the future, many typical industrial case studies can be carried out to study the new phenomena and new laws of industrial innovation ecosystem from the micro perspective, so as to analyze the specific phenomena, formulating the optimal policies. Thirdly, this study uses EWM, which considers only the numerical discrimination degree of the index and ignores rank discrimination. Consequently, future research will pay more attention to reflecting the rank level of indicators in the system.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su14074111/s1, Table S1: Data.

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