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Coupling Coordination and Spatiotemporal Evolution between Carbon Emissions, Industrial Structure, and Regional Innovation of Counties in Shandong Province

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Abstract: Industrial structure and regional innovation have a significant impact on emissions. This study explores, from the multivariate coupling and spatial perspectives, the degree of coupling coordination between three factors: industrial structure, carbon emissions, and regional innovation of 97 counties in Shandong Province, China from 2000 to 2017. On the basis of global spatial autocorrelation and cold and hot spots, this article analyzes the spatial characteristics and aggregation effects of coupled and coordinated development within each region. The results are as follows. (1) The coupling degree between carbon emissions, industrial structure, and regional innovation in these counties fluctuated upward from 2000 to 2017. Coupling coordination progressed from low coordination to basic coordination. Regional differences in coupling coordination degree are evident, showing a stepped spatial distribution pattern with high levels in the east and low levels in the west. (2) During the study period, the coupling coordination showed a positive correlation in spatial distribution. Moran's *I* varies from 0.057 to 0.305 on a global basis. Spatial clustering is characterized by agglomeration of cold spots and hot spots. (3) The coupling coordination exhibited significant spatial differentiation. The hot spots were distributed in the eastern part, while the cold spots were located in the western part. The results of this study suggest that the counties in Shandong Province should promote industrial structure upgrades and enhance regional innovation to reduce carbon emissions.

Keywords: carbon emissions; industrial structure; regional innovation; coupling model

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1. Introduction

The global climate change caused by greenhouse gas emissions is one of the most significant challenges of the 21st century [1]. In accordance with the data disclosed by the International Energy Agency, China is the world's largest emitter of carbon dioxide [2]. Economic growth in China will increase China's total carbon emissions, placing immense pressure on its reduction in carbon emissions [3,4]. Since the importance of climate change and low-carbon economy has been universally recognized, the Chinese government has repeatedly emphasized its commitment to reducing carbon emissions [5,6]. In 2009, the government announced that it would reduce CO_2 emissions per unit of GDP by 40–45% by 2020 [7]. Under the Paris Agreement, China was committed to peaking its carbon emissions by 2030 and achieving carbon neutrality by 2060.

Industrial structure upgrading and technological innovation are recognized as the main driving forces in achieving low-carbon and green development [8–10]. On the one hand, industrial structure upgrading and technological innovation can realize the rational allocation of resources, facilitate the flow of various production factors from capital-intensive industries to technology-intensive industries, and improve the production efficiency of enterprises or industries. On the other hand, as one of the key sources of lower carbon emissions, the interaction between industrial structure and technical progress helps reduce demand-based carbon emissions by eliminating enterprises with low-energy-intensive consumption and technologies and reaching goals of economic development [11–13]. As the largest developing country in the world, China has attached great importance to industrial restructuring and technological progress [14]. According to the Global Innovation Index 2021 released by the World Intellectual Property Organization in Geneva, China continued its progress the previous year and ranked 12th in the world. Meanwhile, according to the Statistical Bulletin of National Economic and Social Development, China's secondary and tertiary industries accounted for 92.7% of its GDP in 2021 [15]. However, the problems such as insufficient scientific and technological innovation momentum and unbalanced industrial structures between regions remain prominent. According to The 2018 Statistical Bulletin of National Science and Technology Funding Investment, China's R&D investment intensity in 2018 was 2.19%, exceeding 2% for five consecutive years. However, a significant gap remains compared with such science and technology powers in the world as the United States (2.79%), Germany (2.91%), and Japan (3.21%). In addition, according to data from the National Academy of Sciences of the United States, China was left behind for 20–30 years by the Unites States in core technologies such as commercial aircraft, semiconductors, and biological machines. These have become the bottleneck factors restricting China's economic development and carbon emission reduction. In this context, exploring the coupled and coordinated relationship between industrial structure, regional innovation, and carbon emissions are of great theoretical and practical significance for China to achieve the emission reduction target by 2030 and promote high-quality development.

With global warming and the greenhouse effect coming to the fore, the low-carbon economy has gradually received widespread attention from scholars at home and abroad. The previous studies can be roughly classified into three categories: the spatiotemporal characteristics of carbon emissions at the different scales or in various industries, the influencing factors of carbon emissions, and the coordination between socio-economy and carbon emissions. In general, existing studies touch upon the spatiotemporal characteristics of carbon emissions at different scales, including the country, regions, cities [16–18]. Zhang et al. constructed the super-efficiency SBM model and Malmquist model to identify the sources of carbon emission performance and driving factors in China's eight economic regions [19]. Wang et al. studied the carbon emission efficiency of 30 provinces in China from 2004 to 2016 [20]. Chen et al. analyzed the spatial differences in carbon emissions and their influencing factors in 286 prefecture-level-and-above cities in China [21]. Nonetheless, little attention is paid to carbon emissions at a finer scale, such as the county level. As the basic unit of China's national economy and administrative system [22], counties are critical for understanding regional heterogeneity and making policies that effectively reduce carbon emissions [23]. In addition, some researchers discussed the influencing factors of carbon emissions. Since the factors influencing carbon emissions are complex and diverse, scholars often use different models to analyze the drivers of carbon emissions, including the Logarithmic Mean Divisia Index (LMDI), input-output analysis, and econometric methods [24–26]. For example, Wen and Huang employed the LMDI decomposition model to decompose the factors affecting carbon emissions into the industrial structure, energy intensity, energy structure, and per capita GDP [27]. Zhao et al. explored carbon emission allowance among various industries/sectors in China through input-output analysis, showing that the most significant share of emission reduction was the electricity and heating sector [28]. Li et al. found that industrial structure upgrading could reduce the carbon emission intensity of the region and its neighboring regions by constructing a spatial panel [29]. In recent years, the coordination between socio-economy and carbon emissions has drawn extensive attention. These studies explore the coupling between carbon emissions and various factors. The improvement in economic development level helps to reduce carbon emissions [30]. The industrial structure dominated by the secondary industry is the main reason for carbon emissions. Technological innovation can effectively reduce carbon emissions by improving the efficiency of energy utilization [31]. The impact of population agglomeration due to urbanization on carbon emissions is uncertain [32]. Foreign direct investment indirectly affects carbon emissions through intermediate variables such as technological innovation and industrial structure [33]. In addition, globalization, environmental regulation, and energy structure are also important factors affecting carbon emissions [34–36]. However, little is known about the overall interaction between carbon emissions, regional innovation, and industrial structure. Furthermore, many existing studies focus primarily on the interaction and integration between two of the three factors, such as carbon emissions and regional innovation, carbon emissions and industrial structure, or regional innovation and industrial structure.

In summary, the existing research on carbon emissions is systematic and productive. There has been extensive and thorough analysis of factors affecting carbon emissions, which provides a theoretical support and reference for this study. Nevertheless, they still have limitations. One the one hand, most studies on the measurement of carbon emission coupling concentrate on the relationship between carbon emissions and a single factor. Little attention is paid to the interaction between carbon emissions, regional innovation, and industrial structure. The interaction and mutual feedback between the latter two have a specific impact on carbon emissions. The three factors also exhibit a spatial effect; however, existing studies tend to focus on national and provincial scales due to the lack of data. Few scholars have examined the coordination degree and spatial spillover effects of the three factors at the county level. Therefore, after clarifying the coupling mechanism between carbon emissions, industrial structure, and regional innovation at the county level, this paper constructs a coupling coordination degree model to explore the coupling coordination degree between carbon emissions, industrial structure, and regional innovation at the county level in Shandong Province, and analyzes its spatiotemporal differentiation using spatial analysis tools, and clarifies its spatial distribution pattern, change trend, and internal law. It provides policy support and a reference for strengthening the green low-carbon and high-quality development, improving the carrying capacity and public service level, enhancing the comprehensive service capacity, promoting the green production ways and lifestyles, and realizing the goals of carbon peaking and carbon neutrality at the county level. At the same time, it can also provide more and better emission reduction ideas for counties in other countries around the world to achieve the goals of carbon peaking and carbon neutrality, and promote the "China solution" for low-carbon development of counties.

2. The Relationship between Carbon Emissions, Industrial Structure, and Regional Innovation

2.1. Industrial Structure and Carbon Emissions

There is a strong correlation between industrial structure and carbon emissions whereby the proportion of the three industries and the conditions within each industry affect carbon emissions. First of all, in the early stage of economic development, the secondary industry dominated by heavy industry accounts for a large proportion of the economic structure where most of the high-energy-consuming sectors are concentrated, and its carbon emissions are also the highest among the three industries [37]. In the middle and late stages of economic development, technology-intensive industries with high-tech as the core are gradually developed, and the intensity of environmental pollution drops significantly. The optimization and upgrading of the economic structure ease the pressure of environmental pollution. The focus of development shifts to the tertiary industry with the modern service industry and high-tech as the core, and the industrial structure is adjusted towards low-carbon and service-oriented industries. The output value of the tertiary industry continues to increase, and that of the secondary industry gradually declines, thereby reducing carbon emissions in related activities throughout the economic life cycle [38]. Secondly, within the industrial structure, traditional industries and low-tech industries have large energy demands and carbon emissions due to the low level of technological innovation. Emerging industries and high-tech industries gradually replace traditional industries and low-tech industries, thereby upgrading the industrial structure. The production efficiency and energy utilization efficiency are correspondingly improved [39].

Therefore, without considering other goals, carbon emissions can be effectively reduced by restricting high-emitting industries and expanding low-emitting industries.

2.2. Regional Innovation and Carbon Emissions

The impact of regional innovation on carbon emissions is mainly achieved through technological innovation. It is generally believed that using alternative clean energy, improving energy efficiency, and using carbon capture and carbon storage technologies are the main ways to reduce carbon emissions, whereby technological innovation or regional innovation is inseparable. Firstly, regional innovation reduces resource and energy use. Innovation can generate new manufacturing technologies and processes, introduce new production methods for goods or services, accelerate the production and promotion of energy-saving products, and reduce the consumption of resources and energy in the process of production and life, thereby reducing carbon emissions [40]. Secondly, regional innovation improves the efficiency of resources and energy utilization. Innovation can provide technical support for the resource recycling industry. The research and development of resource and energy recycling technologies, such as biomass energy technology, water resource collection, and recycling technology, can improve the utilization efficiency of resources and energy, thus reducing carbon emissions [41]. It is undeniable that the development of regional innovation also increases human intervention in nature, accelerates the development of human resources, and leads to the depletion of many non-renewable resources, which cause the growth of energy consumption and carbon emissions [42].

2.3. Industrial Structure and Regional Innovation

The relationship between industrial structure and regional innovation is where information, technology, capital, knowledge, talents, and other elements interact and coordinate with each other in the process of industrial structure transformation and upgrading. New processes and new products created by regional innovations gradually develop into new industrial sectors and industries. Relying on technological advantages, these new production sectors or industries continue to expand in scale, rapidly occupy the market through forward and backward linkage effects, and grow into leading industries. In the meantime, due to the slow technological development and the loss of production factors, traditional production sectors are gradually squeezed out of the market by emerging industries, and emerging industries rise and replace old industrial sectors, resulting in a transformation of the industrial structure [43]. The transformation of the industrial structure will bring forward innovation needs such as new technologies, new methods, and new processes, and innovation needs sometimes prompt the rapid development of the industry. For example, in order to meet market needs and increase market share, enterprises must improve the quality of products and services. This will encourage enterprises to increase human, financial, material, and technological investment, reintegrate various resources, upgrade equipment and process technology, accelerate the introduction of high-quality talents and high-end technology, and increase the quantity and quality of regional innovation investment, thereby promoting regional innovation [44].

3. Materials and Methods

3.1. Study Area

Shandong Province is located along the eastern coast of China, at the lower reaches of the Yellow River. It is located within 34°22′9″ to 38°24′01″N and 114°75′5″ to 122°42′3″E. Shandong Province consists of 17 prefecture-level cities and 136 county-level administrative regions. In view of the feasibility and completeness of data collection, the study combines municipal districts into urban areas, resulting in 97 research units (as shown in Figure 1). In 2017, Shandong Province had a total land area of approximately 157,901 km^2, a population of 10.06 million, and a regional GDP of RMB 726.34 billion [45]. The carbon emission was 835.82 million tons in 2017, making it the largest contributor to China's total carbon emissions [46].

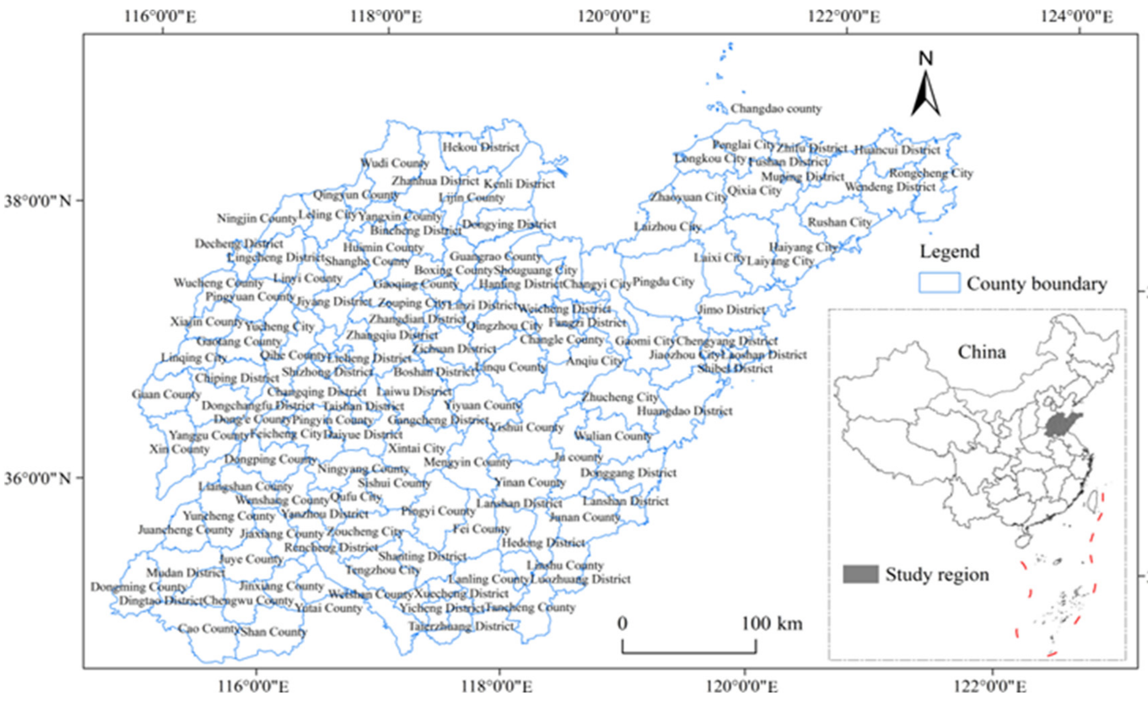

Figure 1. Location map of Shandong Province.

3.2. Data Source

The data used to evaluate the coupled coordination between carbon emissions, industrial structure, and regional innovation in counties were mainly obtained from the China County Statistical Yearbook (2001–2018), the Shandong Provincial Statistical Yearbook (2001–2018), the Shandong Provincial Economic and Social Development Statistical Bulletin, the State Intellectual Property Office, and the Carbon Emission Accounts and Datasets.

3.3. The Evaluation Indicator System

3.3.1. Carbon Emission

The data on carbon emissions of these counties were mainly derived from the Carbon Emission Accounts and Datasets (https://www.ceads.net.cn (accessed on 17 December 2021)). These data were accurate, consistent, and continuous, which were estimated by DMSP/OLS and NPP/VIIRS satellite imagery.

3.3.2. Industrial Structure

Industrial structure refers to the share of agriculture, industry, and services in the structure of a country's economy. The industrial structure can reflect the mode and direction of economic development, which is closely related to the level of carbon emissions. Here, the value added of the secondary and tertiary industries was used to measure the industrial structure.

3.3.3. Regional Innovation

Scientific and technological innovation refers to the inventive and creative capability of enterprises and individuals in a particular sector and technological field in a region. It is an essential driving force for the regional economy and an important factor influencing industrial structure and carbon emissions. The number of patents can indicate the level of invention and creation and the innovation vitality of a region or an enterprise. Hence, the invention patents, utility model patents, and design patents were employed to assess regional innovation.

3.4. Research Methods

3.4.1. Coupling Coordination Model

Coupling, a physical concept, can be defined as a phenomenon in which two or more systems interact and influence each other [47]. The degree of coupling indicates the degree to which the system or elements interact with each other [48]. Carbon emissions, industrial structure, and regional innovation of a county are interlinked, mutually reinforcing, and inseparable from each other. Studying the coupling and coordination between the three factors is very important to determine how to reduce energy consumption and emissions at the county scale. Therefore, this study used the coupling coordination degree to analyze quantitatively the interaction and influence between carbon emissions, industrial structure, and regional innovation at the county scale. Firstly, the raw data were normalized to the equation below in order to eliminate the effect of magnitude:

For positive indicators:

$$X_{ij} = \frac{\max x_i - x_{ij}}{\max x_i - \min x_i} + 0.0001 \quad (1)$$

For negative indicators:

$$X_{ij} = \frac{x_{ij} - \min x_i}{\max x_i - \min x_i} + 0.0001 \quad (2)$$

X_{ij} is the normalized variable; x_{ij} refers to the original value of region i in year t; max x_i and min x_i represent the maximum and minimum values of the jth indicator, respectively.

After the standardization, a coupling coordination model was constructed to measure the orderliness and coordinated coupling between carbon emissions, industrial structure, and regional innovation of 97 counties of Shandong Province. The model is as follows:

$$C = \left[\frac{U_1 \times U_2 \times U_3}{(U_1 + U_2 + U_3)^3} \right]^{\frac{1}{3}} \quad (3)$$

$$T = \sqrt[3]{\alpha U_1 + \beta U_2 + \gamma U_3} \quad (4)$$

$$D = \sqrt{C \times T} \quad (5)$$

Here, C is the coupling degree; U_1, U_2, and U_3 represent carbon emissions, industrial structure index, and the level of regional innovation, respectively; T refers to the comprehensive reconciliation index of carbon emissions, industrial structure index, and the level of regional innovation, respectively; α, β, and γ represent the weight of carbon emissions, industrial structure index, and the level of regional innovation, respectively [49]. This article considers the three equally important; hence, $\alpha = \beta = \gamma = 1/3$; D stands for the coordination degree. Based on the classification by Tian [50], this article divides the coupling coordination degree into five categories (Table 1).

Table 1. Classification of coupling coordination degree.

D Value Interval	Coupling Coordination Type
$0 \leq D < 0.2$	No coordination
$0.2 \leq D < 0.4$	Low coordination
$0.4 \leq D < 0.6$	Basic coordination
$0.6 \leq D < 0.8$	Good coordination
$0.8 \leq D < 1$	Excellent coordination

3.4.2. Global Spatial Correlation

According to Tobler's first law of geography, the closer the spatial distance, the greater the correlation between the attribute values and the stronger the spatial dependence [51].

The global spatial correlation is used to analyze the distribution characteristics of research objects in the global space, which can reflect the regional autocorrelation and spatial agglomeration of certain element attributes [52]. The equation is expressed as follows:

$$I = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} (x_i - \overline{x})(x_j - \overline{x})}{S^2 \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}} \quad (6)$$

where I represents the global spatial correlation index. The range of I is $(-1, 1)$. When $I \in (0, 1)$, there is a positive spatial correlation; when $I \in (-1, 0)$, there is a negative spatial correlation; when $I = 0$, there is no correlation. n is the total number of regional samples; x_i and x_j represent the observed values of coupling coordination degree in county i and j; $\overline{x}$ stands for the mean coupling coordination degree; w_{ij} refers to the spatial weight matrix; S^2 is the sample variance.

3.4.3. Getis-Ord Gi*

Getis-Ord Gi* is one of the most widely used statistical analysis exploration of local measures of spatial association [53]. This index can be used to identify high values (hot spots) and low values (cold spots) of different spatial units [54]. The Z-score and p-value in Equation (7) could determine the spatial location where the hot spots and cold spots occur [55]. Therefore, Getis-OrdGi* was used to analyze the spatial position of the coupling coordination agglomeration of carbon emissions, industrial structure, and the regional innovation of the 97 counties. The measurement model is as follows.

$$G_i^*(d) = \frac{\sum_{j=1}^{n} w_{ij} x_j}{\sum_{i=1}^{n} x_i} \quad (7)$$

where the meaning and calculation of the parameters are the same as in Equation (6).

4. Results

4.1. Trend and Distribution of Carbon Emissions, Industrial Structure, and Regional Innovation

On the basis of Figure 2, carbon emissions in Shandong Province showed prominent spatial imbalances. In 2000, the carbon emissions in all counties were at a low level, except for the Jinan City District, where the carbon emissions exceeded 5 million tons. The rapid expansion of the industrial economy in Shandong Province has increased the demand for energy. The regional economic imbalance has become increasingly evident, contributing to the increase in absolute differences in carbon emissions between different regions. The spatial unevenness of carbon emissions in 2007 increased significantly compared to 2000. More specifically, the carbon emissions of the eastern and central parts were relatively large, forming two high-value centers in Jinan and Qingdao. The counties in the north and south, such as Shouguang, emitted more than 10 million tons of carbon dioxide in 2017. As a group, counties in the western part, such as Qingyun, Ningjing, and Wucheng, had the lowest level of carbon emissions within 5 million tons.

Based on the actual economic data of the 97 counties, the innovation and industrial structure upgrading indexes were calculated. In this article, the average annual value of the innovation and industrial upgrading indexes in each research unit was used to illustrate the overall trend of innovation and industrial upgrading in Shandong Province during the study period (Figure 3). Both indexes showed the same trend, suggesting a correlation between 2000 and 2017. More specifically, the industrial upgrading index maintained a slow upward trend, ranging from 0.65 to 0.90. The industrial structure of Shandong Province was highly developed in recent years. In particular, the share of the primary sector decreased; the share of the secondary sector remained stable; and the share of the tertiary sector increased.

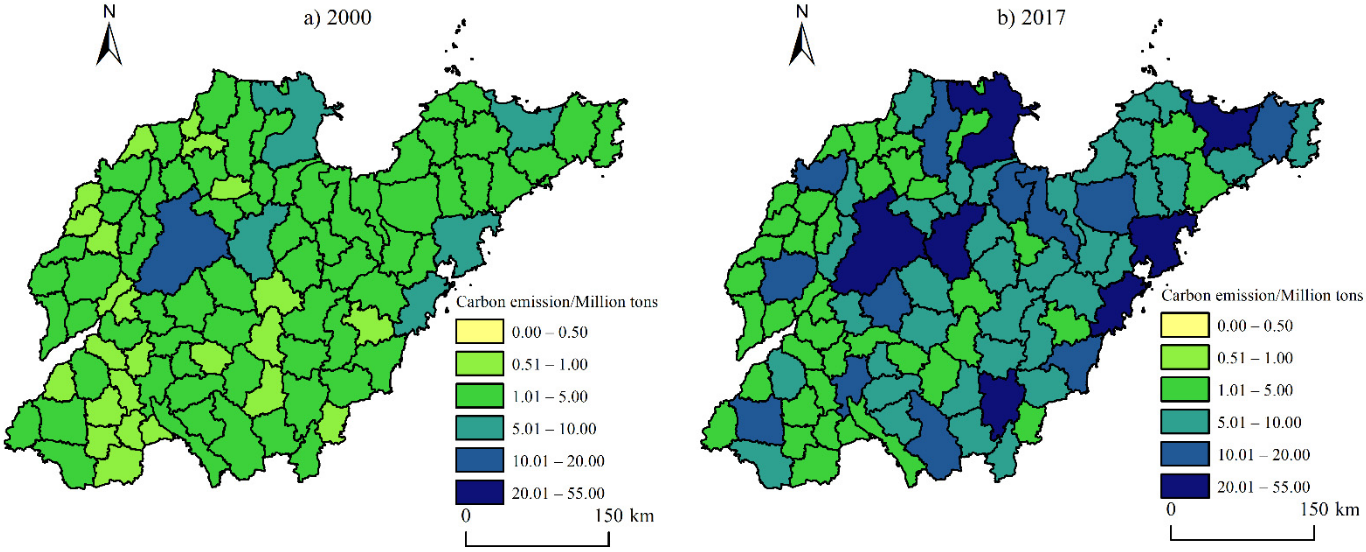

Figure 2. Spatial distribution of carbon emission of the counties in Shandong. (**a**) Spatial distribution of carbon emission of the counties in 2000; (**b**) Spatial distribution of carbon emission of the counties in 2017.

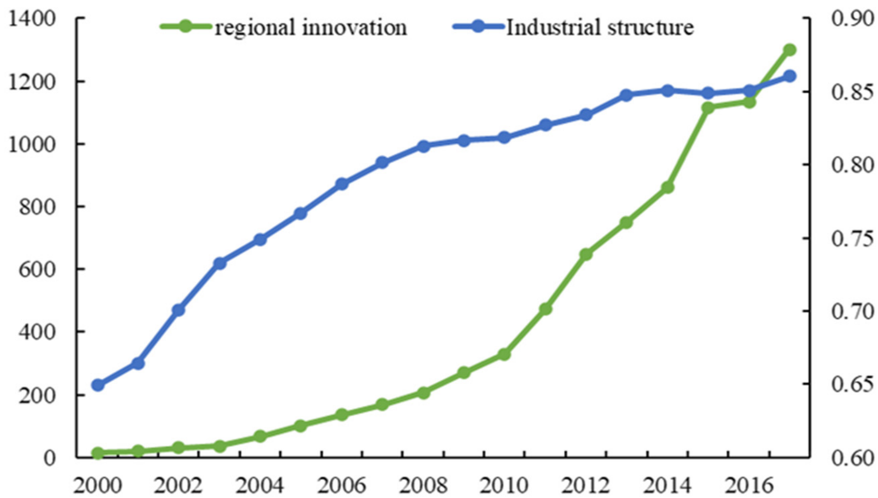

Figure 3. The evolution of regional innovation and industrial structure in Shandong Province from 2000 to 2017.

In parallel, the number of granted patent applications, which indicates the level of regional innovation, showed a steady upward trend. This was closely related to Shandong Province's vigorous promotion of an innovation-driven development strategy. It was also a result of increasing investment in R&D manpower, the increase in regional innovation output, and the promotion of regional innovation capability. Both the industrial structure and regional innovation in Shandong Province exhibited an elevated trend during the study period, though the development rates and levels were similar. The development of regional innovation and industrial upgrading appeared to be more balanced during the study period. To achieve economic transformation from high-speed growth to high-quality development, Shandong Province must continue to increase the investment in regional innovation, encourage the flow of innovation resources, accelerate the transformation and upgrading of traditional industries, and continually increase the proportion of high-tech industries.

4.2. Temporal Trend of the Coupling Coordinating Degree

The coupling coordination degree between carbon emissions, industrial structure, and regional innovation in Shandong Province increased from 0.22 to 0.50 between 2000 and 2017, as shown in Figure 4. In the period 2000 to 2017, the average coupling coordination degree was 0.36, indicating that the three systems counterbalanced each other and did not achieve an ideal state of coupling. Numerically, the coupling coordination degree improved from low coordination to basic coordination. It could be divided into two stages based on the classification of the coupling coordination degree and its fluctuations. (1) From 2000 to 2010, the coupling coordination degree was relatively low, always less than 0.40. It showed a gradual upward trend. Thus, the overall synergistic effect of the three systems was manifested as low coupling coordination, which was in the middle of coordination and incoordination. It was the rapid industrial development and the crude economic development model in Shandong that produced a large amount of carbon dioxide in the early 21st century. However, the enterprises in Shandong Province exhibited a low innovation awareness and failed to invest in energy savings and emission reduction technologies. As a result, there was a breaking-in period within the three systems, which did not substantially contribute to one another. The degree of coupling coordination between the three systems changed from low coordination to basic coordination from 2011 to 2017. During this period, Shandong's economy was optimized and upgraded, and its regional innovation capacity was enhanced. The growth rate of carbon emissions slowed down, resulting in a relatively tight coupling between the three systems. This indicated that the interaction between the three systems was further enhanced; the synergistic effect was evident; and it began to develop in a healthy and orderly manner. Nevertheless, it has not yet reached a level of good coupling coordination. The degree of coupling coordination between the three systems could be further enhanced.

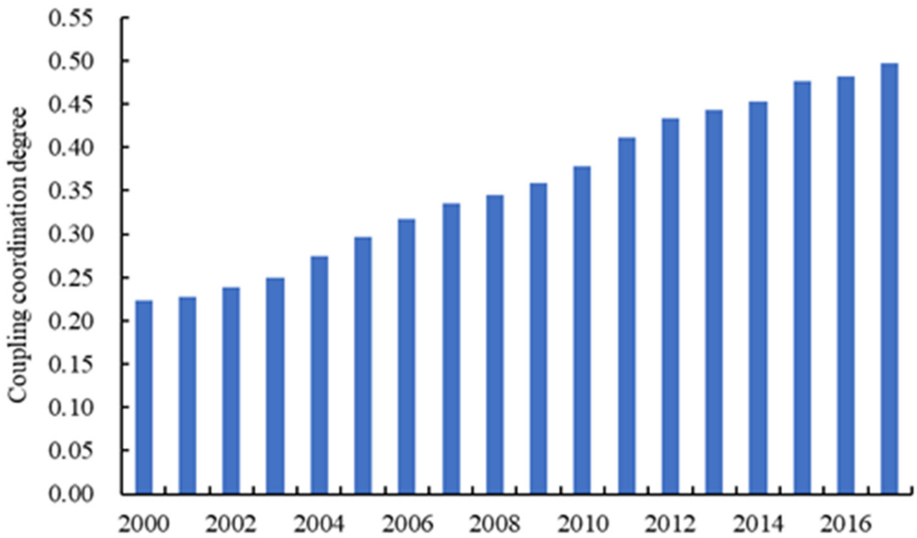

Figure 4. The spatiotemporal evolution of the coupling coordination degree.

As the proportion of each type of coupling coordination increased, it appeared that the level of coordination between carbon emissions, industrial structure, and regional innovation began to cross into phases as shown in Figure 5. The average coupling coordination of the 97 counties was 0.22 in 2000. The highest proportion of low coordination was 60.82%. A total of 95.87% of counties had a value below 0.40 and therefore were classified as years of low-level development. The year 2012 marked a turning point in the evolution of coordination types over time. The coordination between carbon emissions, industrial structure, and regional innovation gradually increased from 2012 to 2017. As the proportion of low coordination decreased, the share of basic coordination increased, becoming increasingly dominant. Good coordination and excellent coordination occupied a certain position and fluctuated year to year. The two varied from 2.06% and 0.00% in 2012 to 12.37% and 1.03% in 2017. Globally, the proportion of basic coordination (equal to or greater than 0.40) increased, while the proportion of no coordination (less than 0.20) declined.

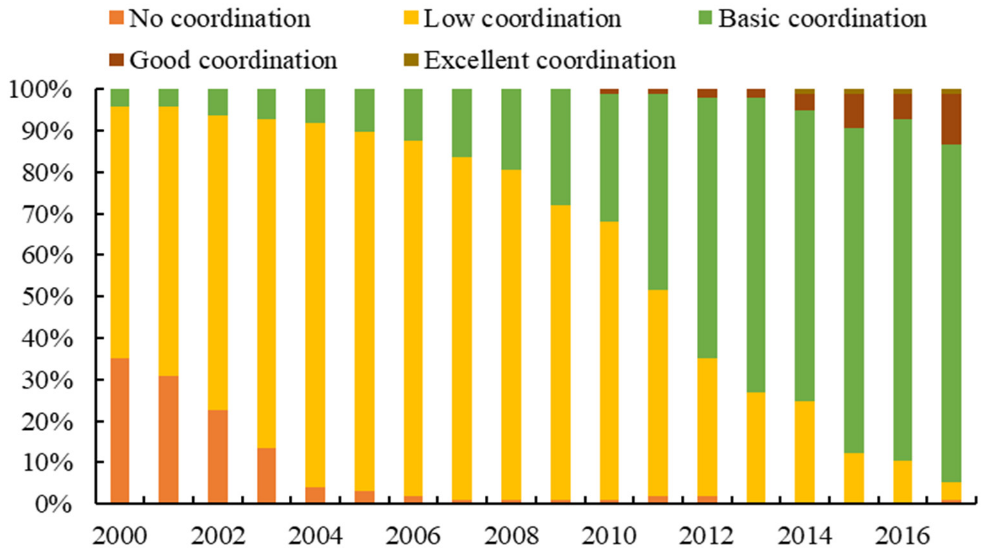

Figure 5. The proportion of each type of the coupling coordination degree in counties of Shandong in 2000–2017.

4.3. Temporal Evolution of the Coupling Coordination Degree

In this study, the coupling coordination degree of carbon emissions, industrial structure, and regional innovation of the 97 counties in Shandong Province from 2000 to 2017 was measured using the coupling coordination model. Using ArcGIS 10.8 software, this study plotted the spatial distribution of carbon emissions, industrial structure, and regional innovation for each county in Shandong Province between 2000 and 2017. The results were used to analyze the spatial differences in the coupling coordination degree (Figure 6).

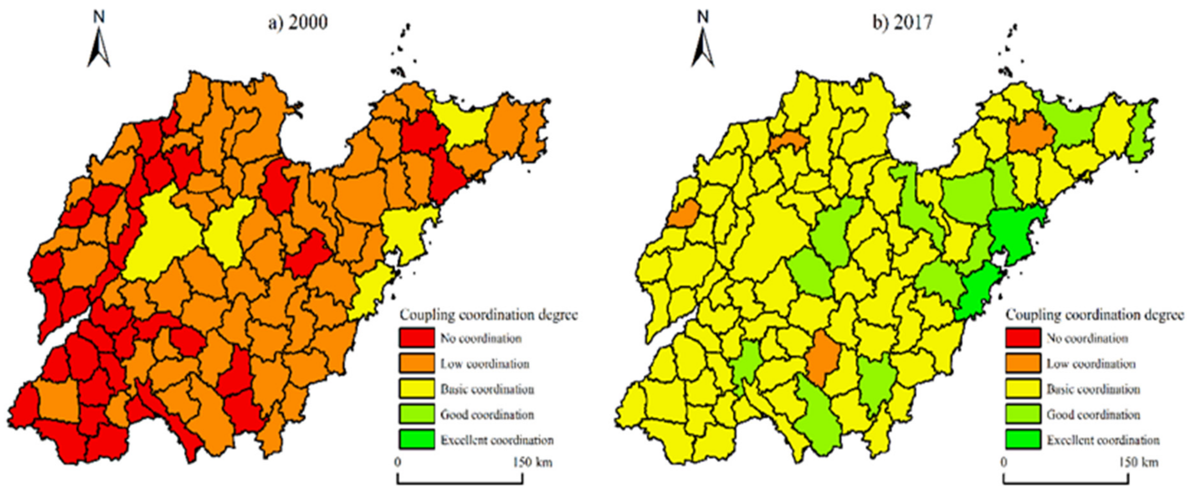

Figure 6. The spatial distribution of the coupling coordination degree. (**a**) The spatial distribution of the coupling coordination degree in 2000; (**b**) The spatial distribution of the coupling coordination degree in 2017.

From the perspective of spatial distribution patterns, the coupling coordination degree in Shandong Province from 2000 to 2017 showed an overall upward trend. In 2017, there was a higher degree of coordination between carbon emissions, industrial structure, and regional innovation of all counties in Shandong than there was in 2000, when there was apparent spatial variability. More specifically, in 2000, the coupling coordination degree for all counties, which was less than 0.60, was not satisfactory. There were three types of coupling coordination in 2000. A total of 34 counties did not coordinate, accounting for 35.05% of the total number of counties. The main reason for this was that the carbon emissions in these counties was generally high. The poor spillover effects during this period resulted in a lower degree of mutual influence and coordination between carbon emissions, industrial structure, and regional innovation. A total of 59 counties, such as Jvnan, Yucheng, and Tancheng, had a low level of coupling coordination, accounting for 60.82% of the total. There were 4.12% of counties with basic coordination, including Yantai City District, Jinan City District, Qingdao City District, and other counties. Compared to 2000, the coupling coordination degree in 2017 increased to varying degrees in all counties. The coupling coordination degree appeared to cluster, indicating that interactions between counties gradually become more significant. There was a decrease in the proportion of counties with no coordination and low coordination from 35.05% and 60.82% to 1.03% and 4.12%, respectively. Between 2000 and 2017, the percentage of counties with basic coordination jumped from 4.12% to 81.44%. From basic coordination to good coordination, Pingdu, Rongcheng, Zhucheng, and the other 12 counties made significant progress. Qingdao City District advanced from basic coordination to excellent coordination.

4.4. Spatial Autocorrelation of the Coupling Coordination Degree

Since there is apparent spatial heterogeneity between carbon emissions, industrial structure, and regional innovation in different counties, it is necessary to perform exploratory spatiotemporal analyses. As a result of constructing the spatial matrix of adjacent weights, Moran's I and test results were calculated using Equation (6).

In accordance with Table 2, we found that the global Moran's I of coupling coordination was > 0, with a positive Z-score and p-value of 0.1, passing the significance test at a 10% level. The results indicated that the coupling coordination degree had remarkable spatial clustering characteristics during the study period. As a result, the global Moran's I demonstrated a trend of first decreasing and then increasing, indicating that the spatial differences displayed certain characteristics by different phases. Between 2000 and 2007, the global Moran's I plunged from 0.1434 to 0.0572, leading to a weakening of the spatial agglomeration trend and a reduction in the significance of spatial development differences. Between 2008 and 2017, the global Moran's I rose from 0.0930 to 0.2571, indicating that regions with high coordination were increasing, and the agglomeration dynamics of regions with low coordination were also increasing. Therefore, the spatial differences in development were gradually becoming more significant.

Table 2. Global Moran's I analysis of the coupling coordination degree.

Year	Moron's I	Z-Score	p-Value	Year	Moron's I	Z-Score	p-Value
2000	0.1434	2.3158	0.0666	2009	0.1080	1.7344	0.0665
2001	0.0876	1.4535	0.0664	2010	0.1321	2.1202	0.0674
2002	0.1027	1.6600	0.0680	2011	0.1503	2.3452	0.0677
2003	0.0835	1.4027	0.0681	2012	0.1815	2.9631	0.0652
2004	0.0974	1.5651	0.0681	2013	0.3076	4.7549	0.0668
2005	0.0924	1.4780	0.0688	2014	0.3073	4.6485	0.0686
2006	0.1042	1.6526	0.0695	2015	0.2973	4.5753	0.0676
2007	0.0572	0.9903	0.0695	2016	0.2465	3.8417	0.0674
2008	0.0930	1.4854	0.0700	2017	0.2571	4.3441	0.0669

4.5. Spatial Distribution Patterns of the Coupling Coordination Degree

According to the global Moran's I of the coupling coordination degree, the counties in Shandong Province displayed a certain degree of spatial clustering overall from 2000 to 2017. Therefore, Getis-OrdGi* could be used to analyze the distribution of hot and cold spots. Using the classification method provided in the Manual of ArcGIS, the hot and cold spots of the coupling coordination degree were divided into four categories: cold spots, sub-cold spots, sub-hot spots, and hot spots (Figure 7).

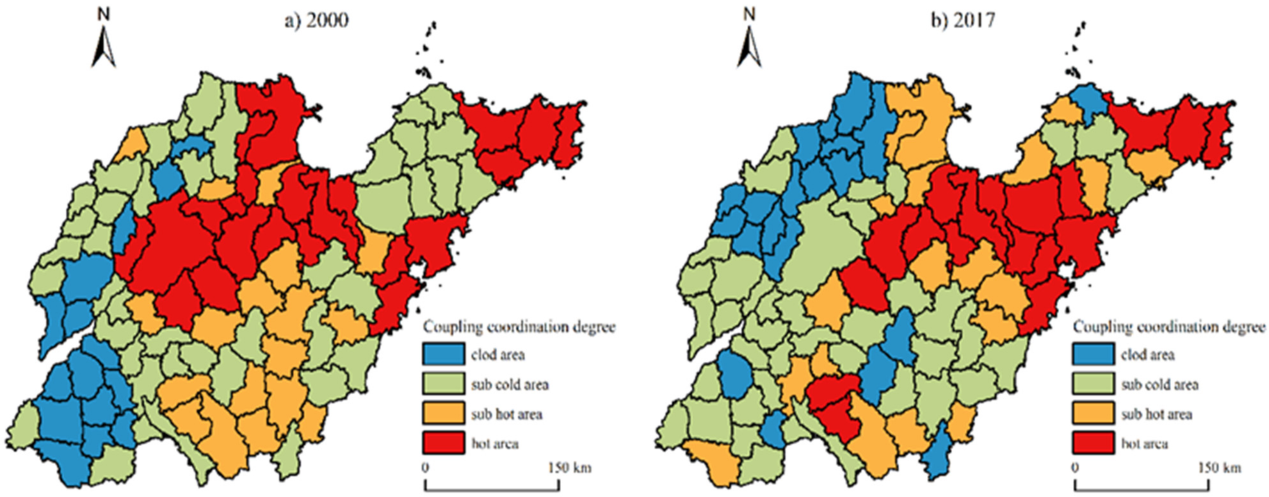

Figure 7. Spatial clustering characteristics of the coupling coordination degree. (**a**) Spatial clustering characteristics of the coupling coordination degree in 2000; (**b**) Spatial clustering characteristics of the coupling coordination degree in 2017.

The number and structure of cold and hot spots displayed considerable spatial heterogeneity during the study period. Hot spots and cold spots accounted for 21.65% and 15.46% of the total counties in 2000, respectively, while sub-hot spots and sub-cold spots accounted for 62.89% of the total counties. Hot spots were mainly located in the eastern and central parts of Shandong Province. Cold spots were primarily located in the western part. Sub-hot spots were primarily found in the southern part. The other areas were sub-cold spots. In 2017, the quantitative structure varied greatly. The number of hot spots decreased from 21 to 17, and the decreasing counties were Rushan, Boxing, Dongying, and Lijin. Cold spots increased slightly from 15 to 21. Tancheng, Pingyi, and Mengyin were converted from sub-hot spots to cold spots in recent years as a result of an increase or decrease in carbon emissions. There were 19 sub-hot spots, mainly located in the peripheral areas of the hot spots. Sub-cold spot areas decreased from 43 to 40, with a more scattered distribution. Most sub-cold spots were located in southern counties.

Overall, the scope of spatial agglomeration and the number of counties in the hot and cold spots changed significantly from 2000 to 2017. During the study period, the number of hot and sub-hot spots declined from 39 to 36, and the agglomeration area of high-value counties narrowed. The Getis-OrdGi* of coupling coordination revealed the spatial distribution of "high in the eastern part and low in the western part". The number of cold spots and sub-cold counties increased from 58 to 61, but the distribution became less concentrated. Hot spots showed a trend of shrinking from central to eastern parts, while cold spots showed a trend of expansion from northeast counties to southwest counties.

5. Conclusions

Sustainable development is greatly impacted by the coordination between carbon emissions, industrial structure, and regional innovation. Studying the 97 counties in Shandong Province with the coupling coordination model, the spatial autocorrelation model, and Getis-OrdGi*, we examined the spatiotemporal evolution and spatial linkage of coupling coordination between the three factors.

During the study period, the degree of coupling coordination between carbon emission, industrial structure, and regional innovation fluctuated upwards. In the period 2000–2011, the degree of coupling coordination was dominated by low coordination. Consequently, the type of coupling coordination degree transformed from low coordination to basic coordination, which meant that the interaction between carbon emissions, industrial structures, and regional innovation was enhanced and developed in a healthy and orderly manner. In these counties in Shandong Province, there were notable differences in the degree of coupling coordination between the three major factors, displaying a stepped spatial distribution pattern of high in the east and low in the west.

The global Moran's I of coupling coordination degree was greater than 0 and passed the significance test. The coupling coordination showed a significant positive spatial correlation, indicating substantial spatial agglomeration. The proportion of counties in hot spots continuously decreased, while the proportion of counties in cold spots increased. Hot spots were primarily located in the north and central parts of the province. In terms of industrial restructuring and regional innovation coordination, these regions had close economic ties and significant spatial spillover effects, increasing the overall level of interregional coupling and coordination. The cold spots were located in the western part. In these regions, economic development was delayed; industrial structure was unreasonably rigid; and innovation capacity was low. There was still room for improvement regarding the upgrading of industrial structure and the improvement of innovation capacity, which in turn affected the degree of coupling coordination between the three factors.

6. Policy Recommendations

To achieve the goals of carbon peaking and carbon neutrality, it is important to understand the interaction rules and evolutionary characteristics of industrial structure, regional innovation, and carbon emissions objectively. As a consequence, the formulation of regional carbon emission reduction policies cannot simply focus on industrial structure or scientific and technological innovation, but must incorporate the coupling and synergistic effects of regional innovation, industrial structure, and carbon emissions. The following policy recommendations were developed based on the above conclusions.

(1) In Shandong Province, it is critical to accelerate the industrial structure upgrade and foster a balanced and coordinated development of industries that are interdependent. In order to improve the efficiency of the allocation of factor resources, the provincial government of Shandong should provide policy incentives, financial support, and other measures to encourage the transformation and upgrading of enterprises. It is the responsibility of Shandong Province to promote the rational arrangement of industries in each county actively. Enterprises should transition from a polluting, low-value-added industry to a high value-added, low-pollution industry, developing regional industrialization toward environmental protection and low-carbon industrialization.

(2) We recommend that Shandong Province should improve local innovation capabilities, as well as a regional science and technology innovation environment. In Shandong Province, each county will be required to increase investment in research funding and promote basic and applied research in universities, firms, and research institutions through policies such as financial incentives, tax breaks, and interest concessions. It is important for each region actively to play the role of innovators composed of universities, enterprises, and research institutions to improve the efficiency of factor utilization. In each region, it is significant to strengthen the relationships between industry, schools, and research institutions to promote the sharing of innovation-related factors such as technology and knowledge through innovation platforms such as research laboratories and engineering centers to bring science and technology innovation to conserve energy and reduce greenhouse gas emissions.

(3) We recommend supporting the development of synergistic innovations in the region and the modernization of industrial structures. Each county in Shandong Province should strengthen the collaboration between regions and improve the training of scientific and technological talents. In order to promote talent flow and resource sharing within the region, an information sharing platform should be developed between counties. In order to decrease the intensity of carbon emissions, each county should take advantage of the advantages of local resources, vigorously develop the local beneficial characteristic indus-

tries, promote regional inventiveness and industrial structure upgrading, and facilitate synergistic development among those areas.

Despite the fact that this study contributes to the knowledge about industrial structure, regional innovation, and carbon emissions to some extent and provides theoretical references for such studies, it still has some limitations. Firstly, the measurement of industrial structure and characterization of regional innovation capacity needs improving due to the aforementioned adjustments of county administrative divisions, the changing nature of the statistical yearbook indicators, and limited data availability. Secondly, due to the limited space, further analysis should be directed towards the portrait and analysis of the spatiotemporal patterns of the coupling coordination of industrial structure, regional innovation, and carbon emissions from a multi-factor and multi-scale perspective. We will discuss their influencing factors, demonstrate the role of different influencing factors, and explain their mechanism of action in the future.

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