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Quantitative Simulation and Verification of the Coordination Curves between Sustainable Development and Green Innovation Efficiency: From the Perspective of Urban Agglomerations Development

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Abstract: Green innovation efficiency is the symbol of competitiveness; sustainable development is an important way to enhance social and economic development comprehensively. By deeply understanding the coordination development law and facilitating the development progress between the two, it has great practical significance for the promotion of sustainable development in China. Based on multi-source data, this paper discusses the basic principle of the climbing rule for the coordination process between sustainable development and green innovation efficiency in urban agglomerations and constructs a mathematical model to obtain its geometric expression. Then, according to the entropy weight model, SBM-DEA model and coordination model, the sustainable development level, green innovation efficiency and coordinated development level are calculated. Finally, through the simulation verification methods, the coordination process and the formation and development process of urban agglomerations are cross-discussed. The results are as follows: (1) The differences in growth rates are the main reason for the spatial distribution mismatch between sustainable development and green innovation efficiency. (2) Highly coordinated regions have gradually extended from the national level to the surrounding low-level urban agglomerations. (3) The coordination level between sustainable development and green innovation efficiency passed the antagonism period and is expected to rise further in the near future and (4) The coordination progress in urban agglomeration is a wave-like climbing curve that changes with the development of urban agglomeration.

Keywords: coordination progress; wave climbing law; co-opetition threshold; simulation and verification; urban agglomerations

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1. Introduction

To balance the contradiction between humans and environments, sustainable development has been widely recognized worldwide [1]. As the most representative developing country, China's practice of sustainable development has considerable influence worldwide [2,3]. Currently, China's social economy is in a new normal stage of development transition [4], and the previous extensive growth model, which excessively pursued the growth rate, is prone to problems such as unreasonable industrial structure and uneven development among regions, which can no longer meet the people's ever-increasing needs for a better life in the new era [5]. It can be seen that the transition path of sustainable development provides an important basis for strategic adjustments to national development [6]. It is not only in accordance with China's new development concept of "innovation, coordination, green, openness, sharing", but also with the rules of national social economic development and the real interests of the people [7]. As one of the five new development concepts in China, innovation is the primary driving force and strategic support for achieving sustainable development, whereas green is the essential condition to achieve sustainable development [8]. With the country's continuous investment in innovation development, input–output efficiency has gradually become an important criterion for measuring the sustainable development level [9]. Meanwhile, as an economic concept, urban agglomeration is not only a spatial carrier to promote sustainable development, but also an area for resource gathering [10]. Discussing the relationship between regional sustainable development and green innovation efficiency will help to remove resource circulation barriers and optimize problems related to unreasonable development structures and uneven distribution of innovation resources. Therefore, the coordination degree between sustainable development and green innovation efficiency in urban agglomerations were accurately measured; the resource integration process for coordination progress between sustainable development and green innovation efficiency among cities was explored; and the dynamic interaction rules between sustainable development and green innovation efficiency was studied. It is not only important for China to implement an innovation-driven strategy and ultimately achieve sustainable development transition, but it also has practical reference significance for countries around the world, especially developing nations, to break through development bottlenecks and coordinate the contradiction between man and nature.

Firstly, sustainable development reflects the harmonious development of a society, economy and ecosystem [11]. It is not only a means for developing countries to break through the development bottleneck, but also a key for developed countries to maintain regional competitiveness in the context of global ecological and environmental constraints [12]. Secondly, green innovation efficiency reflects the green degree of innovation efficiency, which can also be described as "sustainable innovation efficiency" or "environmental-driven innovation efficiency" [13]. It comprehensively considers the balance between ecological and economic benefits in the process of innovation factor input and output [14]. Currently, sustainable development and green innovation efficiency have been individually discussed by numerous studies and analyzed from various perspectives by scholars worldwide [6,15–17]. Sustainable development research is primarily characterized by two main lines: theoretical discussion and quantitative analysis. Firstly, the majority of theoretical research focuses on determining what constitutes sustainable development [18], what the characteristics are and how it may be achieved [19]. Generally, sustainable development differs from traditional high-speed growth in terms of its goals, connotations, value judgments and development requirements [20]. In this respect, sustainable development refers to a model of development that is high-efficiency, green and has long- run growth [21]. As a major factor influencing sustainable development, the importance of innovation drive has been affirmed by authoritative scholars in the fields of regional sustainable development [22,23]. Secondly, most quantitative research focuses on establishing an index system or selecting a single alternative indicator, such as green total factor productivity [24]. For the research around green innovation efficiency, in terms of content, the research focuses on regional differences in green innovation and the factors that influence it, including industrial agglomeration and external economic development conditions [25]. The research areas are primarily national or provincial [26]. In terms of methods, most scholars chose a non-parametric data envelopment analysis model to evaluate the efficiency [26] (Wang and Ren, 2022). Clearly, sustainable development and green innovation efficiency are interdependent [27]. The coordination of sustainable development and green innovation efficiency can significantly benefit society and economy's further development [28]. However, there are only few studies addressing the interaction between the two. Scholars primarily focus on the interaction between the overall green innovation level and sustainable development. For instance, Sun (2022) concluded through a policy analysis model that the progress of green innovation will improve productivity and reduce environmental consumption, which will contribute to sustainable development [29]. Additionally, green innovation involves a more complex innovation process and higher innovation costs compared with traditional technical innovation. Abid and Aftab (2022) proposed that sustainable development can enhance the platforms for green innovation and create spillover effects, and a benign closed loop will be formed between sustainable development and green innovation under the coordination progress [30]. As a consequence of the resource aggregation, the coordination level between sustainable development and green innovation in regional central cities will be higher than surrounding regions, which also leads to an earlier coordination level crossing [31].

Through the summary, it is evident that despite the progress made on the interaction research between sustainable development and green innovation, there are still certain limitations and significant areas for further investigation. Firstly, the existing literature focuses primarily on the interaction between overall green innovation levels and sustainable development [32], rarely discussing the coordination from the perspective of green innovation efficiency, leading to a gap between the measured value of green innovation and its actual significance. Secondly, even though there have been many studies that measured and analyzed green innovation efficiency individually [33], most efficiency measurement models have limitations in radial and angular measurement and did not take stage correlation into account, which ultimately leads to inaccurate measurement results. Additionally, it has been found that few studies have studied the coordination relationship between sustainable development and green innovation efficiency from the perspective of urban agglomerations. Concurrently, the development rules of the coordination between sustainable development and green innovation efficiency under the urban agglomeration has not been well explored.

By applying the principle of risk reduction, this article evaluates the sustainable development of urban agglomeration based on multi-source data, then chose a combined machine learning method to evaluate the green innovation effectivity. As a final step, the coordination progress rules in urban agglomerations will be simulated and verified quantitatively. The logic for article analysis can be summarized as follows: (1) Firstly, through geometric derivation combined with numerical simulation methods, the basic principles of the coordination progress law are analyzed and the related mathematical models are developed. (2) Secondly, a comprehensive evaluation and spatial-temporal analysis of the coordination progress will be carried out based on the coordination model. (3) Additionally, through the construction of the intensity model and the calculation of integration threshold value in urban agglomeration, the evolution process that central city interacts with other cities to improve the coordination degree is quantitatively analyzed. (4) Finally, the coordination climbing trend in the urban agglomerations has been simulated and verified with the mathematical model established by this article. Through the characterization and analysis of urban agglomeration, this paper aims to fill the gap in current research field that lack coordination research from the perspective of green innovation efficiency and the shortage in quantitative verification for coordination development rule, which can further enrich the research around sustainable development and green innovation. It will not only provide a decision-making basis for the coordination development in China, but can also provide scientific reference for countries around the world to break through the bottleneck of economic transition and sustainable development.

2. Research Methodology and Data Processing

2.1. Theoretical Analysis of Coordination Rules in Urban Agglomerations

The formation and development of urban agglomeration are accompanied by the interaction between different ecosystems, such as social, economic and natural resources [34]. As a result of the economic effects produced by the spatial gathering of production factors, surrounding cities have been attracted to interact with the central core city, thereby contributing to the formation and sustainable development of urban agglomerations [35]. Likewise, the coordination progress of sustainable development and green innovation efficiency in urban agglomerations is also a process in which central cities continue to work with nearby cities in order to promote economic structural transition and enhance sustainable development. Particularly, as urban agglomerations form and develop under the radiation effect, the spatial scope expands steadily [36]. However, cities will still be experiencing challenges in coordinating sustainable development and green innovation efficiency [37]. The coordination development progress will be stagnated or even retreated as the resources' agglomeration reaches a certain level [38]. Consequently, the coordination law of sustainable development and green innovation efficiency will gradually experience three phases of antagonism, running-in and coordinated with the expansion of urban agglomerations. The coordination law of sustainable development and green innovation efficiency in urban agglomerations is shown as a wave climbing shape under an irregular arc over time, Figure 1.

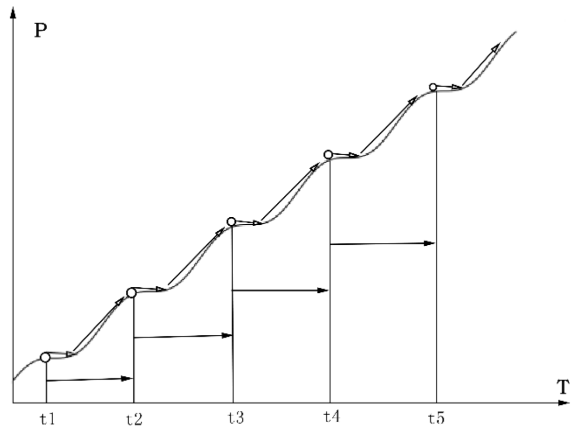


Figure 1. The basic function model of the climbing law.

The description of the regular law progress is shown as follows: In the early stages of urban agglomeration development, when central city A has reached a bottleneck period and it is difficult to continue improving the level of coordination between sustainable development and green innovation efficiency, central city A will take the initiative to unite with surrounding cities B. Consequently, the circulation of green innovation resources and economic development elements within urban agglomerations can be optimized. However, the coordination level of the newly united cities usually lags behind the original cities and the relationship also begins to deteriorate. The coordination level between the sustainable development and the green innovation efficiency in the urban agglomerations gradually declines at this stage. Throughout the co-opetition, the coordination level of the newly united city gradually synchronizes with the original cities, and the coordination level is also enhanced. Throughout the integration and aggregation of resources among cities, a development trend of "1 + 1 > 2" is gradually developed. It is anticipated that the coordinated development of the two cities will further increase the attraction of resources in nearby cities, and that the original urban agglomeration will absorb the new city C as part of its wider coordinated regional development. Under the same concept, central city A continues to unite with neighboring cities B and C . . . N, in order to promote the formation of urban agglomeration between cities A and N-1 cities and optimize resource factors. In the process of integration, the coordination level among cities will also go through the development stage of antagonism-running-coordination, and then the coordination level will finally climb.

This paper draws on the climbing mechanism of sustainable development, and then puts forward the climbing law of the coordination between sustainable development and green innovation efficiency of urban agglomeration. In contrast with the traditional model, the ascending law discussed in this paper is aimed at the development characteristics of the coordinated development in urban agglomerations, that is, under the development process of urban agglomerations, figures out how the internal development factors are reorganized and integrated. However, under the antagonistic period, the coordination level is difficult to be substantially improved or even regressed, so it will show a wave ascending pattern in general. Therefore, it has great practical significance to explore the coordination development law under the formation process of urban agglomerations, which are quantitatively simulated and verified, in order to better serve the layout planning of urban agglomeration in the overall coordinated development, and jointly achieve the strategic goal of China's green economic transformation and sustainable development.

2.2. Geometric Expression of Coordination Rules in Urban Agglomerations

In this paper, an exponential function is selected to reflect the coordination progress of sustainable development and green innovation efficiency, and presents the coordination progress of urban agglomerations as a wave-climbing curve. The curve represents a nonlinear composite climbing curve in which the number of joint cities increases with time, illustrating the dynamic process of agglomeration's coordination wave- climbing capabilities. According to the coordinated evolution law between sustainable development and green innovation efficiency in urban agglomeration, the mathematical function model can be expressed as follow:

$$P_t = kt + e^{|\alpha \sin(\beta t)|} \quad (1)$$

In the formula, P_t represents the level of coordination between sustainable development and green innovation efficiency in period t; k is the slope of linear function and the rate climbing, which represent the rate of coordination change; $k = \Delta P/\Delta t$, Δt are the periods of the function's waves, $\Delta t = \pi/\beta$; α is the amplitude of a trigonometric function, and represents the retardation coefficient of coordination level; β represents the cycle factor for coordinated development; and π/β is the frequency in trigonometric terms.

As the mathematical model derived from the basic principle does not consider the efficiency of the core cities in the early stages of development, this paper further optimizes the curve simulation function to improve the accuracy of the mathematical model. The specific expression of the formula is as follow:

$$P_t = P_0 + k(t - t_0) + \{e^{|\alpha \sin[\beta(t-t_0)]|} - 1\} \quad (2)$$

In the formula, t_0 represents the initial time for coordinating sustainable development and green innovation efficiency in the core cities; P_0 represents the initial value of the coordination level. Essentially, the formula expresses the initial time and the initial potential index of coordination.

In the climbing curve, the climbing rate represents the integration speed of coordination between sustainable development and green innovation efficiency. The climbing rate of the curve was obtained by the derivative, and the specific expression is as follow:

$$p'_t = \begin{cases} k + \alpha\beta \cos[\beta(t - t_0)]e^{\alpha \sin[\beta(t-t_0)]}, t \in \left[\frac{2k\pi+\beta t_0}{\beta}, \frac{\pi+2k\pi+\beta t_0}{\beta}\right] \\ k - \alpha\beta \cos[\beta(t - t_0)]e^{-\alpha \sin[\beta(t-t_0)]}, t \in \left[\frac{\pi+2k\pi+\beta t_0}{\beta}, \frac{2\pi+2k\pi+\beta t_0}{\beta}\right] \end{cases} \quad (3)$$

In the formula, p'_t represents the curve's climbing rate and P_t's integration speed. The above optimized formula can be used to draw the simulated wave climbing function curve for coordination between sustainable development and green innovation efficiency, as shown in Figure 2.

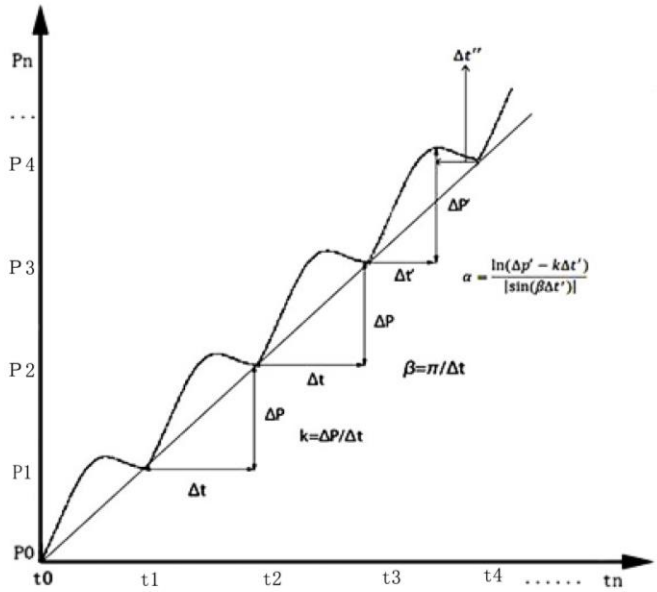


Figure 2. Climbing curve for coordination in urban agglomerations.

2.3. Research Methods

2.3.1. Entropy Methods

In the comprehensive calculation of various sub-indicators for sustainable development, the weight of sub-indicators will affect the authenticity of the evaluation results [39]. Therefore, this paper uses information entropy to assign the index weight quantitatively, which avoids the problems of guesswork and randomness brought by the subjective evaluation method, and makes the index weight more in line with the objective reality. Under the entropy method, the function of each index is determined by the value of the index v_{nm}. When the value of an index is 0, the index will not play a role in the comprehensive evaluation. Therefore, this paper first carries out dimensionless processing on the index data, then calculates the weight using the entropy method.

Calculate the proportion of the m index of the n urban agglomeration:

$$x_{nm} = \frac{v_{nm}}{\sum_{n=1}^{y} v_{nm}} v_{nn} \epsilon \left(u_i, z_j, u_k\right) \tag{4}$$

Calculate the index information evaluation entropy:

$$e_m = -\frac{1}{in(y)} \sum_{n=1}^{y} \left[x_{ij} \times in(x_{nm})\right],\ m = \{1, 2, 3, \cdots, x\} \tag{5}$$

Calculate the redundancy of information:

$$d_m = 1 - e_m \tag{6}$$

Calculate the index weight:

$$W_m = \frac{d_m}{\sum_{m=1}^{x} d_m},\ m = \{1, 2, \cdots, x\},\ W_m \epsilon \left(a_i, b_j, c_k\right) \tag{7}$$

Calculate the overall index:

$$S_i = \sum_{j=1}^{m} w_m x_{nm},\ (n = 1, 2, \ldots, x) \tag{8}$$

2.3.2. Slacks-Based Model Data Envelopment Analysis

At present, data envelopment analysis is commonly selected in the study of efficiency measurement, which is mostly used to measure the efficiency value of single output [40]. However, due to the complexity and comprehensiveness of the research subject, a single output indicator is not adequate [41]. Therefore, this paper will adopt multiple indicators and add the inevitable environmental pollution products in the innovation development process as the undesired output to scientifically measure the green innovation efficiency of each city. The Slacks-based model is modified based on the traditional DEA model to achieve the comprehensive measurement of multiple indicators, so that the measurement value is more consistent with the concept of green innovation [42]. Therefore, based on the SBM-DEA (Slacks based model-data envelopment analysis) method, this paper takes each city in the urban agglomeration as a single production decision-making unit and includes three parts: input, desired output and undesired output. The model established as follow:

$$S_v^t\left(x^{t,k'}, y^{t,k'}, b^{t,k'}, g^x, g^y, g^b\right) = \max_{s^x, y^x, s^b} \frac{\frac{1}{N}\sum_{n=0}^{N}\frac{s_n^x}{g_n^x} + \frac{1}{M+1}\left[\sum_{m=1}^{M}\frac{s_m^y}{g_m^y} + \sum_{i=1}^{I}\frac{s_i^b}{g_i^b}\right]}{2} \tag{9}$$

$$st \sum_{k=1}^{K}\lambda_k^t x_{km}^t + s_n^x = x_{k'n}^t, \forall n; \sum_{k=1}^{K}\lambda_k^t y_{km}^t + S_m^y = y_{j'n}^t, \forall m, \sum_{k=1}^{K}\lambda_k^t b_{ki}^t + S_i^b = b_{k_t'}^t, \forall i; \tag{10}$$

$$\sum_{k=1}^{K}\lambda_k^t = 1, \lambda_k^t \geq 0, \forall k; s_n^t \geq 0, \forall n, s_m^y \geq 0, \forall m, s_j^b \geq 0, \forall i; \tag{11}$$

S_v^t represent the directional distance function, $x^{t,k'}, y^{t,k'}, b^{t,k'}, g^x, g^y, g^b$ and s_n^x, S_m^y, S_i^b are the input-output factors, direction vector and the relaxation vector of city k'; and s_n^x, S_m^y, S_i^b reflect the deviation of the optimal distance to the observation point.

2.3.3. Coupling Coordination Model

Based on the existing studies' results of the coupling model [43,44], this paper firstly constructs the coupling model between sustainable development and green innovation efficiency in urban agglomerations. The model is constructed as follows:

$$C = \left(\frac{E_1' \times E_2'}{E_1' + E_2'}\right)^{\frac{1}{n}} \tag{12}$$

In the formula, C represents the coupling degree between sustainable development and green innovation efficiency, and the value ranges from 0 to 1′ E_1' and E_2' represent the sustainable development and green innovation efficiency calculated values, respectively; and n is the number of sub-systems.

It is still important to note that this model has several drawbacks. For example, when it has similar evaluation scores for subsystems, the calculated coupling function value will be extremely high regardless of the overall level of evaluation [45]. Based on the perspective of urban agglomeration, this paper explores the coupling and coordination level between sustainable development and green innovation efficiency, which not only needs to observe the coupling situation, but also requires high-level and sustainable coordinated development. Therefore, this paper improves the coupling degree model to become a coupling and coordination model, and is shown as follows:

$$\begin{gathered} D = \sqrt{C \times T} \\ T = \alpha U_1' + \beta U_2', 0 \leq T \leq 1, 0 \leq D \leq 1, \alpha + \beta = 1 \end{gathered} \tag{13}$$

In the formula, D represents the coordination degree between sustainable development and green innovation efficiency, with the values ranging from 0 to 1. T represents the general coordination index, and α and β are the parameters.

Finally, by summarizing the relevant coordination studies and fully considering the measurement results of coordination between sustainable development and green innovation efficiency [46], this paper classifies the coordination degree, as shown in Table 1.

Table 1. Classification criteria of coordination degrees.

Coordination Degree	Development Status	Status Information
$D = 0$	Uncoordinated	System is not coupled overall and the development is not coordinated
$0 < D \leq 0.3$	Barely disordered	System coupling is extremely low and it is on the verge of an unbalanced development
$0.3 < D \leq 0.5$	System antagonism	System coupling is generally low and the coordinated development is insufficient
$0.5 < D \leq 0.8$	Barely coordinated	System coupling is relatively moderate and it is in a relatively good status of coordinated development
$0.8 < D \leq 1$	Highly coordinated	System coupling is fairly high and it is undergoing a coordinated development process of sustainability

2.3.4. Co-Opetition Intensity and Threshold Model

Firstly, the intensity of co-opetition refers to the intensity of mutual attraction and integration between sustainable development and green innovation efficiency among cities [17]. The intensity of co-opetition is positively correlated with the coordination level and negatively correlated with the distance between cities. Now, the co-opetition intensity model is constructed based on the basic function model of coordination, and the formula is shown as follows:

$$F_{xy} = \frac{\sqrt{C_x \times C_y} \times \sqrt{G_x \times G_y}}{D_{xy}^2} \times \frac{1}{100} \quad (14)$$

In the formula, F_{xy} represents the co-opetition intensity for coordination between city x and city y; C_x and C_y represent the coordination level in city x and city y; G_x and G_y represent the GDP of city x and city y; D_{xy}^2 is the distance between city x and city y. Considering the unified range standard during the drawing process, this paper reduces the value of co-opetition intensity by 100 times in order to make an intuitive comparison.

Secondly, the co-opetition threshold refers to the critical value when sustainable development and green innovation efficiency begin to achieve mutual attraction among cities [47]. Within the urban agglomeration, cities with complementary resources have the demand and tendency to unite and obtain new resources [48]. However, the cities' united process still takes time to integrate and digest, so there is objectively a resource integration threshold to determine whether a core city can combine with a new city to integrate [49]. Based on Fang et al. (2019)'s method for threshold value setting [17], this paper selected the mean value of co-opetition intensity as the threshold value, and the formula is shown below:

$$\lambda_{xy} = \frac{1}{2} \times \frac{\sum_{x=1}^{m} \sum_{y=1}^{n} F_{xy}}{x \times y} \quad (15)$$

In the formula, λ_{xy} represents the co-opetition threshold values; F_{xy} represents the co-opetition intensity; x is the total number of evaluated years; and y is the total number of cities in the evaluated urban agglomeration.

2.4. Index System

2.4.1. The Evaluation System for Sustainable Development

Compared with the traditional evaluation of economic development, sustainable development reflected the combination of long-term strategic and short-term goals, which is a comprehensive development process of economic sustainability, social sustainability and environmental sustainability [50]. Therefore, by referring to Zhang and Chen (2021)'s basic concept of the construction of a sustainable development system, this paper selects relevant index data from three basic aspects of economic volume, economic structure and economic benefits to set up a comprehensive evaluation system of sustainable development, and then applied the entropy method to calculate the indicator weights and the overall index, as seen in Table 2.

Table 2. Comprehensive evaluation system of sustainable development.

A Target Layer	B Criterion Layer	C Index Layer	E Weight
Comprehensive index of sustainable development	social sustainability	Elastic coefficient of construction land expansion	0.1152
		Disposable income per capita	0.1401
		Doctors per thousand people	0.0899
		University students per thousand people	0.1157
		Electricity consumption per capita	0.1564
	economic sustainability	Fiscal expenditure in GDP	0.0283
		The unemployment rates	0.0118
		GDP output per square kilometer	0.0357
		Level of income coordination	0.084
		GDP energy consumption	0.0142
	environmental sustainability	Sewage treatment rate	0.0142
		Waste disposal rate	0.0192
		PM 2.5 average annual concentration	0.0352
		Carbon emissions	0.135
		Proportion of green area	0.0051

2.4.2. The Evaluation System for Green Innovation Efficiency

At the regional scale, green innovation efficiency measurements require an accurate assessment of urban innovation capability and highlighting green attributes [26]. Therefore, based on the difference in connotation between green innovation efficiency and traditional green productivity, this study fully considers the emphasis on labor and capital in the Cobb–Douglas production function and highlights the green production attribute of inputs [27]. Additionally, since green innovation is characterized by dual spillover effects, which are knowledge spillover and environmental protection spillover, the output should include both innovation output and environmental output [51]. The evaluation system is shown as Table 3.

Table 3. Evaluation index system of green innovation efficiency.

A Target Layer	B Criterion Layer	C Index Layer
Input	Funding input	Expenditure on science and technology
		Expenditure on education
	Labor input	Science and technology service personnel
		Students in colleges and universities
	Resources–energy input	Industrial electricity consumption
		Industrial water supply
		Industrial land area

Table 3. *Cont.*

A Target Layer	B Criterion Layer	C Index Layer
Output	Desired output	Number of green innovation patents
		New product sales revenue
	Undesired output	Discharge of wastewater
		Carbon dioxide emissions
		Soot and dust emission

2.5. Study Area

This paper determines the distribution of urban agglomerations in China by referring to the "19 urban agglomerations development planning" documents issued and approved by The State Council, the National Development and Reform Commission and the governments of all provinces, including national-level urban agglomeration under the following key constructions: Yangtze-river delta (YRD), Pearl-river delta (PRD), Beijing-Tianjin-Hebei (BTH), Middle reaches of Yangtze river (MRYR) and Chengdu-Chongqing (CY); Regional-level urban agglomeration under steady construction: Shandong peninsula (SDP), Guangdong-Fujian-Zhejiang coastal area (YMZ), Zhongyuan (ZY), Guanzhong plains (GZ), Central-south of Liaoning (CSL), Harbin-Changchun (HC), Northern gulf (NG), Northern slope of Tian mountain (NST); Prefecture-level urban agglomeration under construction guidance: Dianzhong (DZ), Qianzhong (QZ), Jinzhong (JZ), Lanxi (LX), Huhhot-Baotou-Erdos_Yulin (HBEY) and Ningxia along the yellow river (NXAY), for a total of 203 cities that were studied as basic units, as shown in Figure 3.

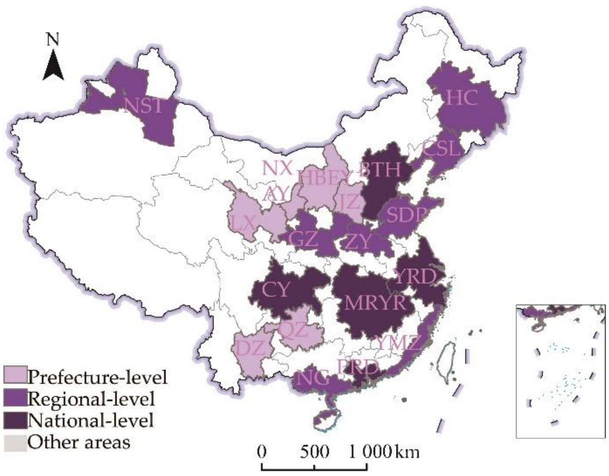


Figure 3. Distribution map of Urban Agglomerations.

2.6. The Data Source

Based on the documents issued by the State Council, the National development-reform commission and provincial governments on the construction of urban agglomerations, this article selects 19 major urban agglomerations in China as the study area. The basic vector data were collected from the National catalogue service for geographic information (www.webmap.cn) accessed on 18 July 2022, and the distribution of each urban agglomeration was determined by ArcGIS. The rest of the indicator data mainly consists of the following aspects:

Database platform. The number of green innovation patents and sales revenue of new products in this paper were obtained from the Chinese research data services (www.cnrds.com) accessed on 21 July 2022. A great number of well-known professors in the field were deeply involved in collecting, arranging and presenting the platform data, making it widely used by multidisciplinary scholars [52].

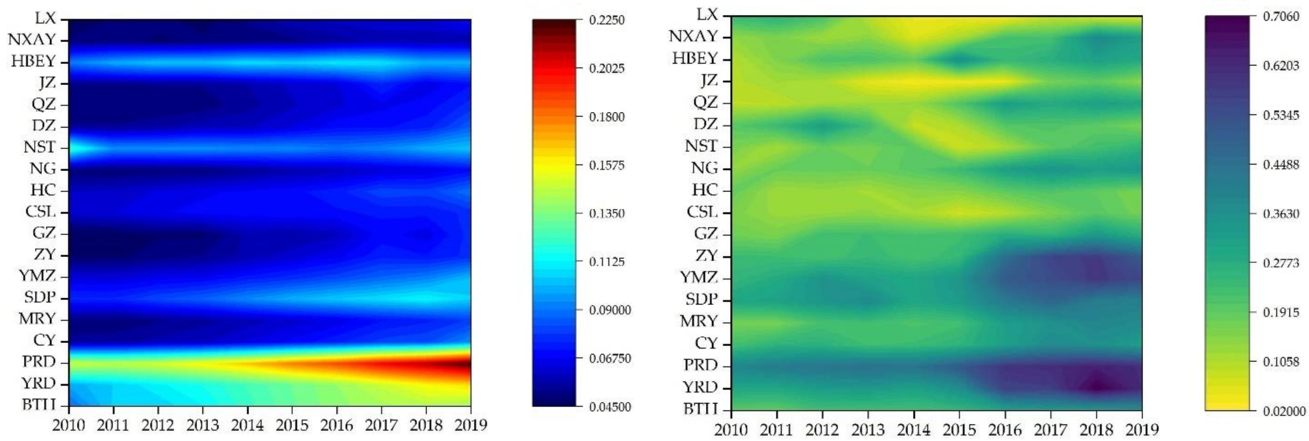
Scientific data. The carbon emission data in this paper were obtained from the published articles of Scientific data. For the data processing, the initial data of carbon emission is the data of county-level units [53]. This paper classified and summarized it according to the city administrative code and subordinate cities, and obtained the carbon emission data of the required urban agglomerations at the city level.

Statistical data. The social, economic and environmental data in this paper were selected from the China urban statistical yearbook, China regional economic yearbook and China construction yearbook from 2011 to 2022. Due to the inconsistency of the original data indicators, this paper adopts a dimensionless method to standardize the index units, and a few missing values are covered by average interpolation.

3. Results

3.1. Quantitative Analysis of SD and GIE

In order to visually present the magnitude evolution law of sustainable development (SD) and green innovation efficiency (GIE) in urban agglomerations, the estimated values of sustainable development and green innovation efficiency are matrixed by Origin and are shown in the form of Planar heat map, as shown in Figure 4a,b.



(**a**) (**b**)

Figure 4. Development trends of SD (Sustainable development) and GIE (Green innovation efficiency) in urban agglomerations.

From the perspective of magnitude distribution (Figure 4a), there was a relatively good performance for national-level urban agglomerations. The high-value areas were concentrated in the Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta urban agglomerations, which have created a significant gap with other urban agglomerations. Among the national-level urban agglomerations, the Pearl River Delta urban agglomeration has the highest value of sustainable development, having reached 0.225 at the end of the study period. Among the regional-level urban agglomerations, except Shandong Peninsula, Guangdong-Fujian-Zhejiang and the Northern slope of Tianshan, the rest of the urban agglomerations were mostly in the value range of 0.07 to 0.08. with no significant gap between each. The prefecture-level urban agglomerations generally recorded a lower level of sustainable development. Except for the Huhhot-Baotou-Erdos-Yulin urban agglomerations, which exceed 0.1, the rest of the urban agglomerations are all in the lowest range of development. In general, the spatial distribution of sustainable development in urban agglomerations presents a relatively obvious magnitude ladder pattern. From the perspective of quantity climbing, the overall urban agglomerations show a linear upward trend, with an average growth rate of 4%. Except for the northern slope of the Tianshan, which fluctuated and regressed over the observed years, the rest of the urban agglomerations have climbed to varying degrees. The average climbing rate for Chengdu-Chongqing and Guanzhong urban agglomeration reached 6.5%, which achieved the most significant improvement in sustainable development among all urban agglomerations. Overall, regional-level urban agglomerations gradually closed the gap with national-level urban agglomerations in terms of the climbing rates. However, there are still spaces remaining for prefecture-level urban agglomerations to catch up, and the growth rates and improvements for the prefecture-level urban agglomerations are not obvious under the observation range.

From the perspective of magnitude distribution (Figure 4b), the Pearl River Delta and Yangtze River Delta are the only two urban agglomerations that exceed 0.6 in green innovation efficiency. Compared with the other two first-tier national-level urban agglomerations, the Beijing-Tianjin-Hebei urban agglomeration significantly lagged in green innovation efficiency, with an efficiency value of only 0.34, even lower than some urban agglomerations at the prefecture-level. The rest of the urban agglomerations with low efficiency are mostly distributed in the northwest, northeast and southwest regions. It is evident that city attributes and geographical location factors significantly influence the efficiency of green innovation. From the perspective of quantity climbing, except for the central-south of Liaoning urban agglomeration, which recorded a small increase after a large fluctuation during the study years, the average growth rate of green innovation efficiency in other urban agglomerations remained at 5% to 12%. Specifically, most of the prefecture-level urban agglomerations showed an average climbing rate higher than the normal range because of the low magnitude in total. However, the overall green innovation efficiency still has a large amount of space for improvement.

When comparing the characteristics of sustainable development and green innovation efficiency together, it was found that green innovation efficiency has a more obvious staggered distribution and the spatial pattern between sustainable development and green innovation efficiency is not completely synchronized. It has reflected that the improvement of green innovation efficiency not only depends on economic output, but tends to rely on a relatively higher weight of green attributes in the industrial structure, economic composition and innovation contribution. Therefore, as an essential driving source for sustainable development, cross-research on green innovation efficiency and sustainable development from the perspective of urban agglomerations, it has an important strategic significance for promoting the continued development in the region.

3.2. Coordinated Analysis between SD and GIE

Based on the understanding of magnitude performance, this paper now calculates the coordination degrees for different urban agglomerations through Formula (13), in order to further explore the coordination relationship between sustainable development and green innovation efficiency. The coordination degrees were classified according to the classification standard in Table 1. Meanwhile, in order to facilitate the observation of the evolution trend, the years 2010, 2013, 2016 and 2019 were selected for visualization displays, as shown in Figure 5.

From the perspective of spatial distribution, cities in urban agglomerations recorded a significant difference in coordination levels. Only several core cities in national-level urban agglomerations, such as Beijing, Shanghai and Shenzhen, have achieved a relatively high degree of coordination. Sustainable development and green innovation efficiency in these cities started to develop simultaneously. The other cities are mostly in the stage of systematic antagonism to basic coordination, and the overall coordination level is generally low. The barely disordered cities in the urban agglomerations are mostly located in the northeast, northwest and southwest regions, reflecting the location characteristics as “high in the Southeast and low in the Northwest” in general. This phenomenon verifies the importance of geographical location factors, innovation resource agglomeration and economic vitality for coordination development.

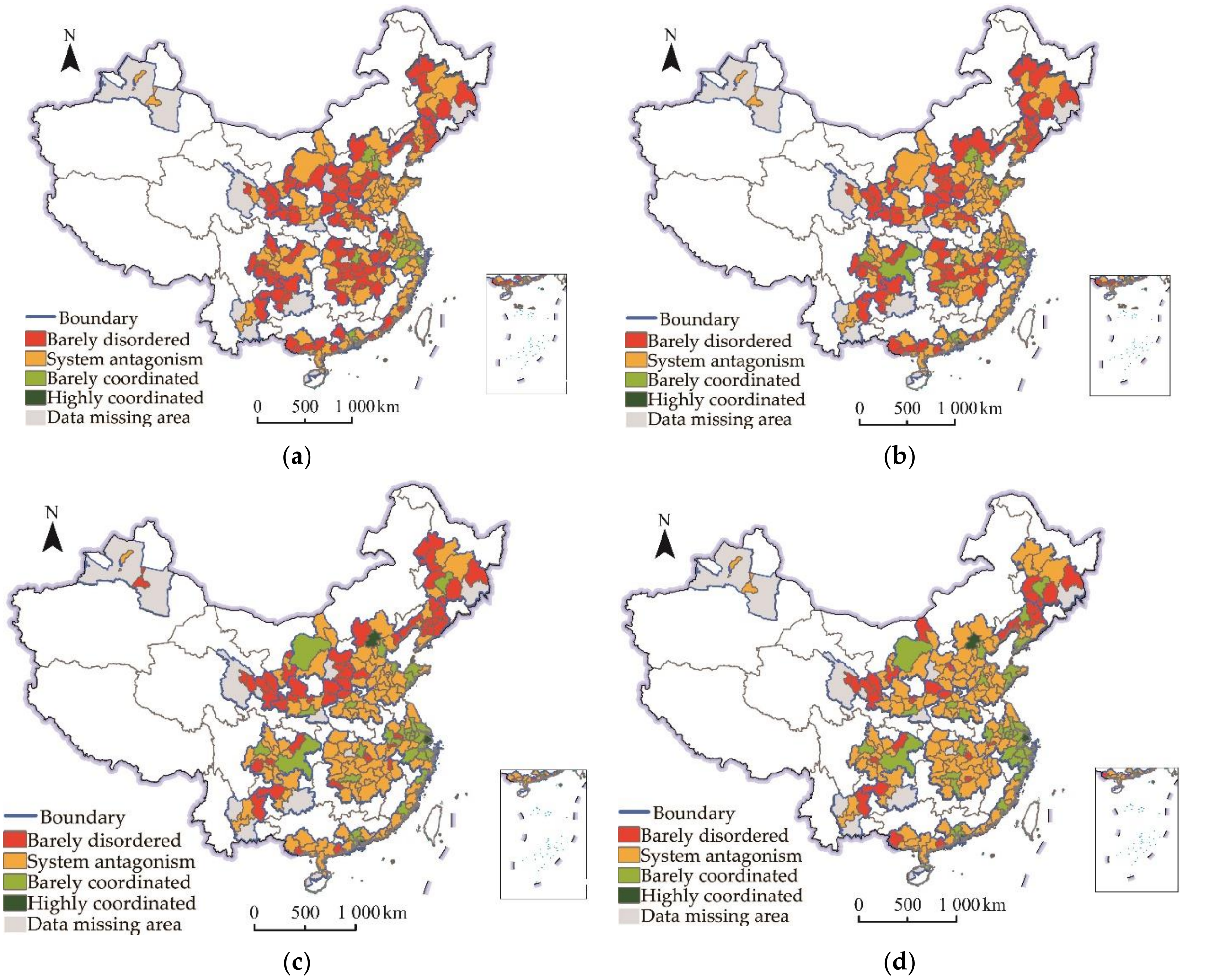


Figure 5. Spatial-temporal evolution trend of coordination level between SD and GIE. (**a**) 2010. (**b**) 2013. (**c**) 2016. (**d**) 2019.

From the perspective of degrees climbing, the coordination between sustainable development and green innovation efficiency in urban agglomerations is at a relatively stable rising stage, but the growth rate is still insufficient. Only a few cities recorded a significant increase in coordination level during the study years, but more than half of the cities were still in the antagonistic stage or below. Specifically, the urban agglomerations in China achieved the greatest coordination improvement from 2013 to 2016 (Figure 5c). Beijing and Shanghai have achieved the leap from barely coordinated to highly coordinated; the uncoordinated cities in the central and eastern areas have also been greatly reduced. By the end of the study periods, only the city of Tongling is still in the barely disordered stage of all the eastern-coastal urban agglomerations, and more than half of the cities in the Yangtze River Delta urban agglomerations reached barely coordinated levels or above. However, the uneven growth rate of cities in different regions still gradually widened the coordination gap in urban agglomerations.

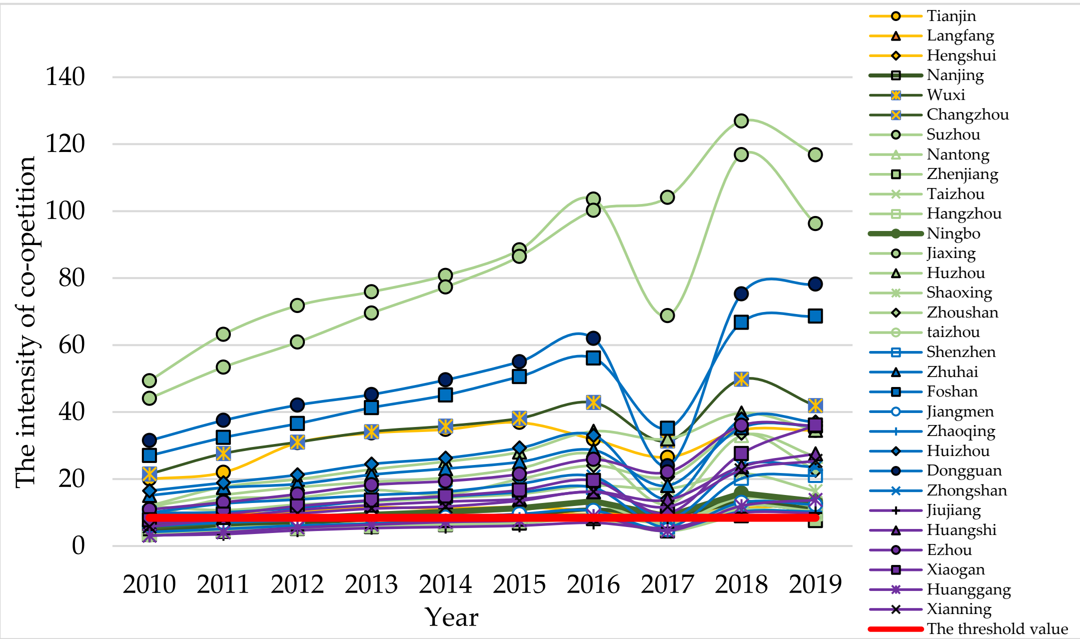
Generally, the coordination regions with high values will gradually extend from national-level urban agglomeration to surrounding regional-level and prefecture-level urban agglomeration. The formation and development of urban agglomerations are corelated to the coordination law of sustainable development and green innovation efficiency. Accordingly, this development trend and spatial distribution pattern confirmed the scientific nature of the Chinese government's positioning and planning for the development of urban agglomerations in China.

3.3. Results Analysis of the Co-Opetition and Threshold

To further discuss the coordination development and the co-opetition situation under the formation of urban agglomerations, Formulas (14) and (15) are chosen to calculate the co-opetition intensity, as well as the threshold value of national, regional and prefecture-level urban agglomerations. Because of the limitation of image space, this paper only shows the cities where the co-opetition intensity for coordination is higher than the threshold value of co-opetition, as shown in Figure 6.

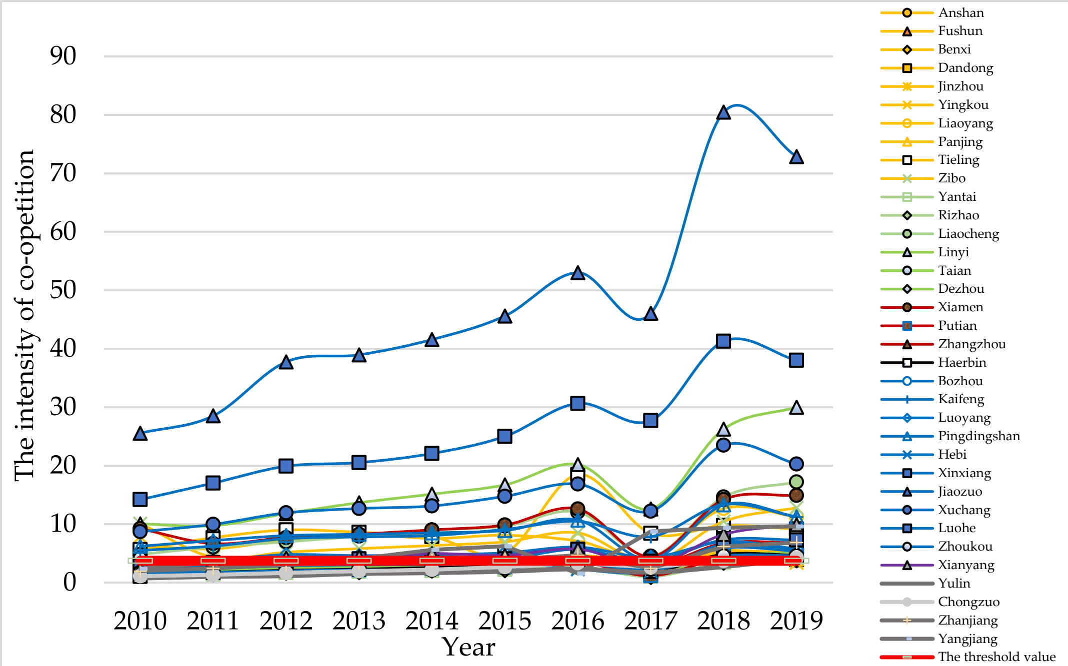
From the perspective of intensity comparison, it can be seen that the co-opetition threshold values of national-level, regional-level and prefecture-level urban agglomeration are 8.434, 3.732 and 1.235, respectively (Figure 6a, Figure 6b, Figure 6c). For national-level urban agglomeration, 31 cities exceed co-opetition threshold values, and both intensity and threshold values are at a relatively high level among all the cities in urban agglomerations of China (Figure 6a). For regional-level urban agglomerations, 35 cities exceed co-opetition threshold values, and even have the advantages in numbers, but there is still a certain gap in threshold values and intensity level, when compared to national-level urban agglomerations (Figure 6b). For prefecture-level urban agglomerations, only 12 cities exceed threshold values, and both intensity and threshold values are at the relatively lowest level among all the cities in urban agglomerations of China (Figure 6c). In general, the urban agglomerations in China exhibit a spatial distribution of co-opetition intensity similar to the spatial distribution of coordination progress.

From the perspective of development trends, the urban agglomerations in China experienced major strategic adjustments in 2017, which caused abnormal changes in the value of co-opetition intensity. Except for this, the co-opetition intensity of three kinds of urban agglomerations all basically showed an increasing and fluctuating trend. Meanwhile, the co-opetition intensity of some cities exceeds the threshold values at the beginning but then drops below through the periods, or rebounds to above at the end. This phenomenon verifies that the coordination progress between sustainable development and green innovation efficiency will go through different stages of antagonism, run-in periods and coordination status with the process of formation and development for urban agglomeration.

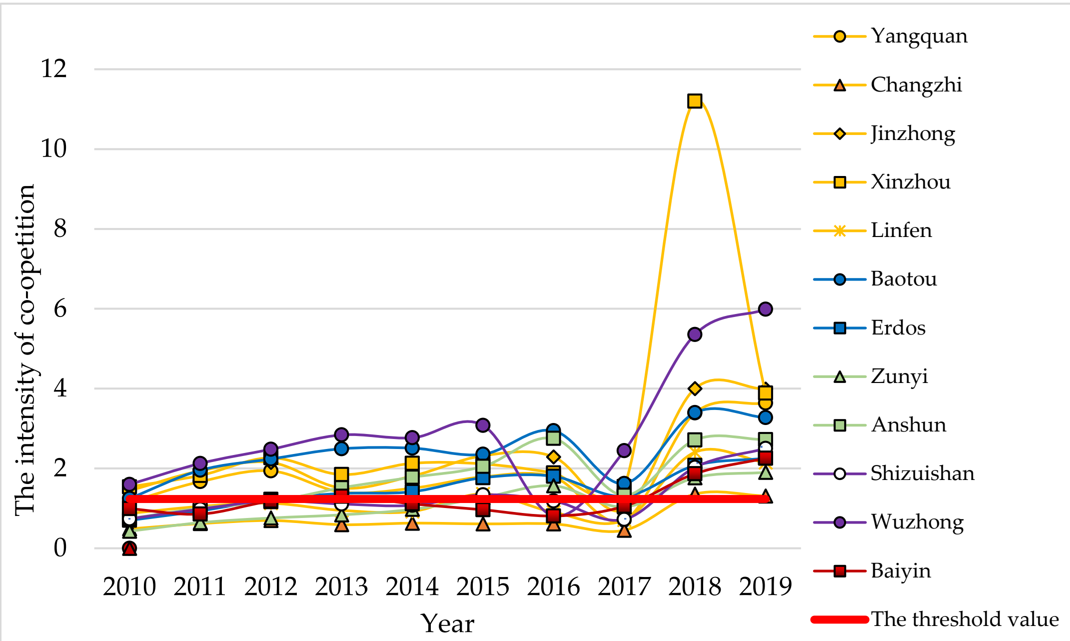


(**a**)

Figure 6. *Cont.*



(**b**)



(**c**)

Figure 6. The evolution map of co-opetition intensity in urban agglomerations. (**a**) National-level urban agglomerations. (**b**) Regional-level urban agglomerations. (**c**) Prefecture-level urban agglomerations.

Based on the evolution trend of the co-opetition intensity in general, it can be seen that the co-opetition intensity of coordination progress is negatively correlated with geographical distance. Furthermore, with the formation and development of urban agglomerations, the co-opetition intensity of urban agglomerations is now in the rising stage after the system antagonism period. The coordination level between sustainable development and green innovation efficiency is expected to rise further.

3.4. Simulation and Verification of Coordination Curve

In the end, in order to verify the credibility of the coordination climbing curve between sustainable development and green innovation efficiency, the waveclimbing function for coordinated development in different urban agglomerations has been fitted several times according to the time series value from 2010 to 2019. The function and the procedure code used for fitting are shown as follows.

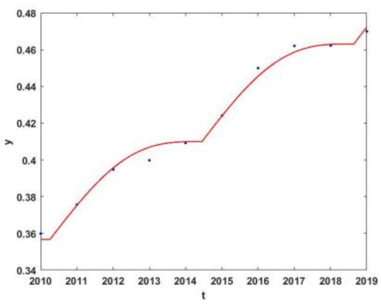
$$P_t = P_0 + k(t - t_0) + \left\{e^{|\alpha \sin[\beta(t-t_0)]|} - 1\right\}$$

```
t = [t0; t1; t2; t3; . . . ; tn];
y = [y0; y1; y2; y3; . . . ; yn];
p = fittype('p0 + k * (t − t0) + (exp(abs(α * sin(β * (t − t0))))−1)', 'independent', 't');
plot(f, t, y);
f = fit(t, y, p);
cfun = fit(t, y, p)
```

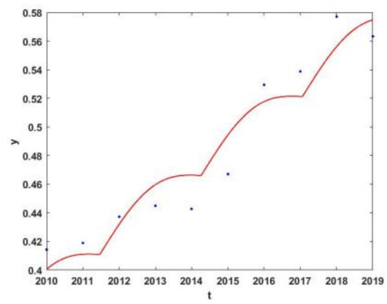
Finally, the optimal function expression of the coordination curve in different urban agglomerations was obtained (Table 4). Based on the table, the fitting diagram for the coordination curve can be drawn (Figure 8).

Table 4. The optimal function expression of coordinated development curve for urban agglomerations.

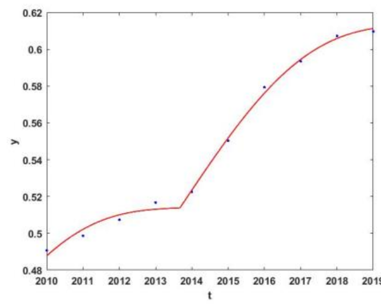
Classification	Urban Agglomerations	The Optimal Function Expression
National-level urban agglomerations	BTH	$P_t = -24.87 + 0.01277(t - 33.56) + \{e^{|-0.0003124 \sin[0.7563(t-33.56)]|} - 1\}$
	YRD	$P_t = -39.07 + 0.01968(t - 6.348) + \{e^{|0.05119 \sin[0.4788(t-6.348)]|} - 1\}$
	PRD	$P_t = 18.57 - 0.00755(t + 447.6) + \{e^{|0.4966 \sin[0.1332(t+447.6)]|} - 1\}$
	CY	$P_t = -25.83 + 0.01139(t + 285.5) + \{e^{|0.02219 \sin[0.6134(t+285.5)]|} - 1\}$
	MRYR	$P_t = 15.6 - 0.006337(t + 399.8) + \{e^{|0.3656 \sin[0.1839(t+399.8)]|} - 1\}$
Regional-level urban agglomerations	SDP	$P_t = -17.98 + 0.009621(t - 103.7) + \{e^{|0.03645 \sin[0.7579(t-103.7)]|} - 1\}$
	YMZ	$P_t = -26.88 + 0.01213(t + 231.4) + \{e^{|0.05547 \sin[0.2145(t+231.4)]|} - 1\}$
	ZY	$P_t = -45.51 + 0.01699(t + 684) + \{e^{|-0.06528 \sin[0.4612(t+684)]|} - 1\}$
	GZ	$P_t = -22.86 + 0.01026(t + 246.6) + \{e^{|0.01496 \sin[0.7431(t+246.6)]|} - 1\}$
	SCL	$P_t = -7.502 + 0.003702(t + 92.35) + \{e^{|0.01954 \sin[0.8702(t+92.35)]|} - 1\}$
	HC	$P_t = -4.916 + 0.002608(t - 18) + \{e^{|0.05365 \sin[0.326(t-18)]|} - 1\}$
	NG	$P_t = -17.3 + 0.01256(t - 611.3) + \{e^{|0.02728 \sin[0.4903(t-611.3)]|} - 1\}$
	NSTM	$P_t = -7.658 + 0.003229(t + 455.5) + \{e^{|0.05303 \sin[0.4158(t+455.5)]|} - 1\}$
Prefecture-level urban agglomerations	DZ	$P_t = -4.816 + 0.002614(t - 60.15) + \{e^{|0.06159 \sin[0.6753(t-60.15)]|} - 1\}$
	QZ	$P_t = -43.64 + 0.01844(t + 367.6) + \{e^{|0.04365 \sin[0.5172(t+367.6)]|} - 1\}$
	JZ	$P_t = -16.38 + 0.007324(t + 248.8) + \{e^{|0.1032 \sin[0.4219(t+248.8)]|} - 1\}$
	HBEY	$P_t = -5.96 + 0.003311(t - 98.42) + \{e^{|0.0117 \sin[0.4531(t-98.42)]|} - 1\}$
	NXAY	$P_t = -24.71 + 0.01114(t + 231.3) + \{e^{|0.006423 \sin[0.7455(t+231.3)]|} - 1\}$
	LX	$P_t = 14.73 - 0.01029(t - 601.7) + \{e^{|0.09232 \sin[0.3601(t-601.7)]|} - 1\}$



7a. BTH

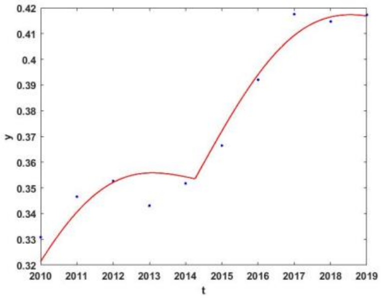


7b. YRD

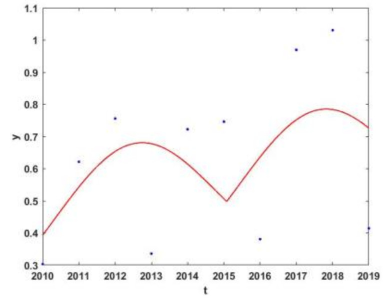


7c. PRD

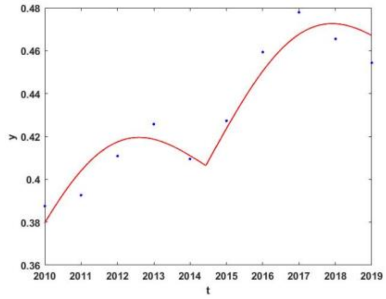
Figure 7. *Cont.*



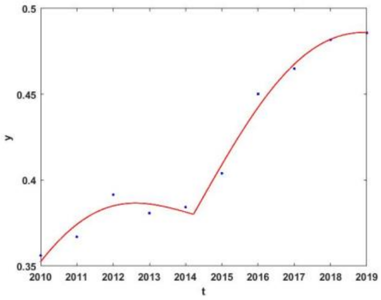
7d. CY



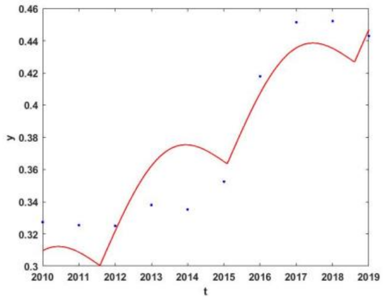
7e. MRYR



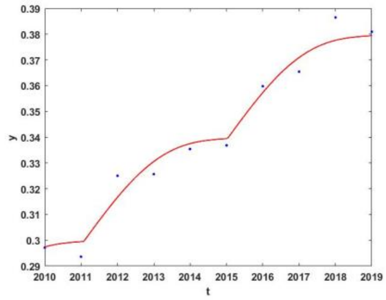
7f. SDP



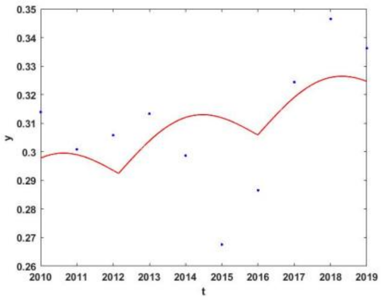
7g. YMZ



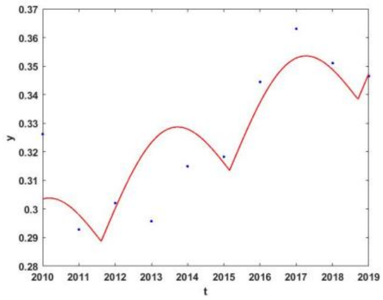
7h. ZY



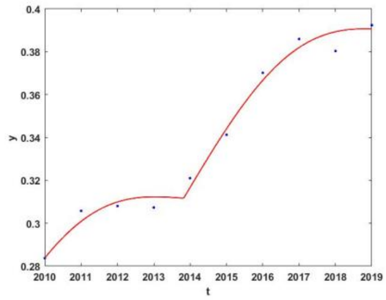
7i. GZ



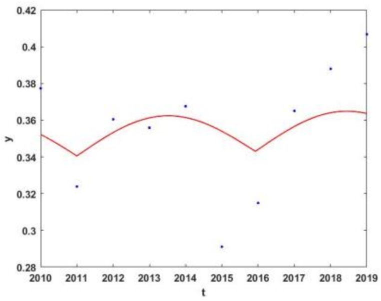
7j. CSL



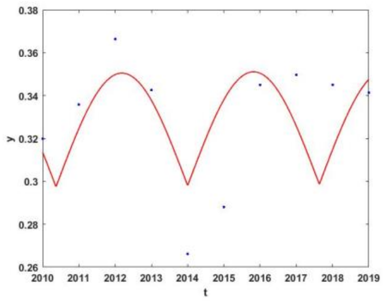
7k. HC



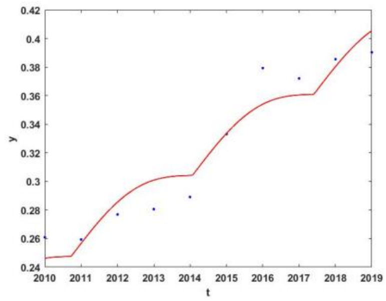
7l. NG



7m. NSTM

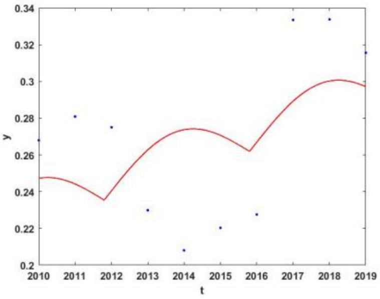


7n. DZ

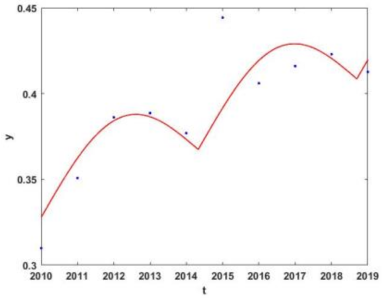


7o. QZ

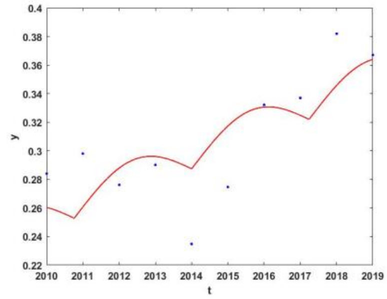
Figure 7. *Cont*.



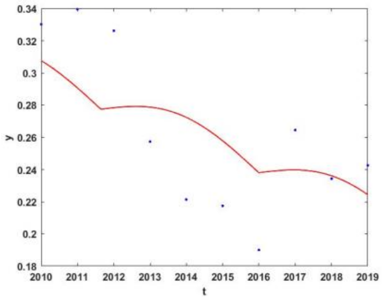
7p. JZ



7q. HBEY



7r. NXAY



7s. LX

Figure 8. Curve fitting diagram of coordinated development law for urban agglomerations.

Throughout the observation, it can be seen that the evolution trend of the fitting map for the coordination curve is similar to the basic function model of the climbing law between sustainable development and green innovation efficiency. The coordination evolution curve in different urban agglomerations presents a relatively well-performed fitting effect, and the results indicate that the coordination between sustainable development and green innovation efficiency in the urban agglomerations follows a wave-like pattern. Through the fitting, the evolution law of the coordination progress between sustainable development and green innovation efficiency in the urban agglomerations has been verified by simulation, which has proved the universal applicability in the development of urban agglomerations. The evolutionary law model can be used to analyze and predict the evolutionary trend of the coordination between sustainable development and green innovation efficiency in urban agglomerations. Based on the analysis, scientific guidance and data support can also be provided for the continued development of urban agglomerations.

4. Discussion

China's social and economic development is currently in a new stage of transition from high speed growth to high quality and sustainable development. However, during the transition process, the lack of new development resources and uncoordinated development among regions have limited the transition to a certain extent, which is urgent for finding a new breakthrough point. Green innovation is an important symbol for a country to maintain competitiveness, and sustainable development is a way to comprehensively improve social and economic prosperity. It has great strategic significance to accurately understand the interaction law between the two and promote their coordination development. Meanwhile, as the main spatial carrier of sustainable development, urban agglomeration is not only the agglomeration area of innovation resources, but also an important experimental area of economic transformation. Therefore, to analyze the coordination process of sustainable development and green innovation efficiency from the perspective of urban agglomeration and master its development law, is the main focus of this paper.

Firstly, by selecting environmental pollution indicators as undesirable outputs, this paper calculated the green innovation efficiency and found differences in the spatial distribution between green innovation efficiency and sustainable development in urban agglomerations. According to Yi et al. (2022)'s research [54], the key factors leading to this phenomenon may lie in the differences in resource endowment and industrial structure between regions. The evaluation of sustainable development focuses on the green economy in terms of volume, whereas the measurement of green innovation efficiency is concerned with the green contribution in innovation output. This discrepancy has led the coordination distribution pattern in the urban agglomerations into a spatial–temporal mismatch in the progress of development. Additionally, the asynchronous improvement between sustainable development and green innovation efficiency in various cities also indirectly caused the difference in coordination climbing degree. Due to the resource aggregation and geographical location advantages, the coordination progress in the national-level urban agglomerations gradually forms a gap compared to the low-level urban agglomerations. This conclusion is similar to Jiang et al. (2020)'s analysis of the spatial characteristics of the coordinated development in urban agglomerations [55], whereby the coordination development in first-tier urban agglomerations shows absolute advantages in general, whereas only regional core cities have shown considerable performance in low-level urban agglomerations. Secondly, Fang et al. (2019) once proposed that core cities will constantly unite with surrounding cities in the formation and development of urban agglomerations, in order to improve the sustainable development in an exponential climbing curve. This article has done the improvement based on Fang et al. (2019)'s model and combined the coordination progress of sustainable development and green innovation efficiency with the formation process of urban agglomeration [17]. It was found that the co-opetition intensity of new united cities in urban agglomeration will complete the intensity climb after the fluctuation around the co-opetition threshold value. The evolution progress shows a wave-climbing trend of gradual coordination after antagonism and run-in stage, which is highly similar to the coordination progress trend between sustainable development and green innovation efficiency. It has proved that the coordination progress of sustainable development and green innovation efficiency in urban agglomeration is also promoted along with the formation and development of urban agglomerations, and the coordination progress and formation of the urban agglomerations are correlated. Finally, the coordination progress wave-climbing curve passed the preset test after several fitting simulations. Meanwhile, the fitted curve is similar to the development trend of the co-opetition intensity and the overall fitting effect is satisfied. The verification results are identical to Fang et al. (2019)'s simulated study about the sustainable climbing capacity curve in Beijing-Tianjin-Hebei urban agglomeration [17]. It is in line with the characteristics of national conditions in China and the reality of regional development, which is universally applicable in the development of urban agglomerations, scientific guidance and data support, which can be provided for the continued development of urban agglomerations.

5. Conclusions

By enriching the diversity of research in an innovative economy and sustainable development, this article wishes to provide a new approach for regional economy or sustainable development scholars to further explore. The main conclusions of this article are as follows:

1. The differences in growth rates are the main reason for the spatial distribution miss-matched between sustainable development and green innovation efficiency. Through the quantitative display by the heat map, it can be seen that the average growth rate of green innovation efficiency recorded rates of 5% to 12% for urban agglomerations, which are higher than the 4% for sustainable development. The overall growth rate of green innovation efficiency is faster than the sustainable development, and this is the main reason for the spatial differences across urban agglomerations.
2. Highly coordinated regions were gradually extended from the national-level to the surrounding low-level urban agglomerations. Specifically, the central cities of the national-level urban agglomeration demonstrate a high degree of coordination, with a rapidly increasing coordination growth rate also; the rest of the cities are mostly at

the stage of system antagonism and are barely coordinated. Because of the uneven climbing levels within each city, the coordination gap between urban agglomerations gradually increases.

3. The coordination level between sustainable development and green innovation efficiency has passed the antagonism period and expected to rise further in the near future. By combining the spatial–temporal evolution map and the evolution map of co-opetition intensity, it can be seen that the co-opetition intensity of coordination progress is negatively correlated with geographical distance. With the formation and development of urban agglomerations, the co-opetition intensity of urban agglomerations is now in the rising stage after the system antagonism period.
4. The coordination progress in urban agglomeration is a wave-like climbing curve that changes with the development of the urban agglomeration. Through the construction and fitting verification of the climbing function curve, it was found that the fitting curves of each urban agglomeration share a high degree of similarity, as well as the development trends of the fitting curves and co-opetition intensities of each city.

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