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Interaction between Urbanization and Eco-Environment in Hebei Province, China

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Abstract: Understanding the complex interaction between urbanization and the eco-environment is necessary for rapid and quality urbanization, eco-environmental protection, and the harmonious coexistence of humans and nature within a region. Based on panel data from Hebei Province between 1985 and 2019, we suggested a symbiosis hypothesis of urbanization and the eco-environment (SHUE) and used the distance coordination coupling model, the Tapio decoupling model, and the symbiosis model to quantitatively determine the interaction relationship between urbanization and the eco-environment. We found that (1) the improved 'Northam curve' of urbanization in Hebei Province met the logistic equation. (2) During the study period, the coordinated coupling degree (CCD) of urbanization and eco-environment exhibited an overall upward trend, while the coupling type gradually changed from the endangered imbalance recession type to the coordinated development type. (3) The decoupling types showed strong and weak decoupling fluctuations, with a high frequency of strong decoupling; the growth rate of the urbanization index was higher than that of the eco-environment index; and there was a positive effect between urbanization and eco-environment indicating positive urbanization. (4) The research results verified SHUE. The symbiosis mode of urbanization and eco-environment was mainly asymmetric mutualism, with the two demonstrating mutual promotion and mutualism. However, in 2016–2019, the symbiosis mode became parasitic, urbanization development enforced upon the eco-environment. The study constructed a set of quantitative method to systematically discuss the interaction relationship from two dimensions: coupling and decoupling. The results provide reference for the coordinated development of urbanization and eco-environment in Hebei Province and consequentially enrich this research field.

Keywords: urbanization; eco-environment; coupling; decoupling

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1. Introduction

Since the Chinese reformation, the country's level of urbanization has significantly increased, with the urbanization rate increasing from 17.9% in 1978 to 64.7% in 2021. China's rapid urbanization has attracted global attention, greatly affecting the world development pattern. Unfortunately, this rapid urbanization has also had many negative consequences, including water shortage [1], energy consumption and CO_2 emission [2,3], and damaged regional ecological service systems [4]. As an engine to promote social and economic development, urbanization is accompanied by many environmental problems, which restrict further urbanization [5]. Since the establishment of the Lowry Model [6], urbanization research has begun to focus on the application of mathematical methods. To predict the level of urbanization, Wlison [7] combined historical data with the moving average method, weighted moving average method, trend prediction method and the exponential smoothing method. In 1975, Northam [8] proposed the 'Northam Curve' that divided urbanization into the initial, rapid, and mature stages. Since then, urbanization research has entered a vigorous development stage [9–11]. There is an elaborate relationship between urbanization and the eco-environment [12]. Exploring this relationship and promoting its coordinated development has become a major issue in academic circles and government departments. This relationship has even been recognized as the frontier field within earth system science research for the next 10 years [13]. As early as 1994, Grossman and Kreuger [14] proposed the Environmental Kuznets Curve (EKC). The curve describes the quality of environmental changes with the improvement of urbanization [15]. Since its introduction, many scholars have studied the coupling relationship between urbanization and eco-environment subsystems, such as water resources, atmospheric environment, energy, and climate [16–19]. Based on the system theory paradigm, several econometric models, such as the coupling coordination degree model, grey correlation degree model and the Tapio model have been used to explore the interactive stress relationship between urbanization and the eco-environment [20–25]. In the study of this coupling relationship, the research area and eco-environment evaluation indexes tend to differ [26–31] and the study area is also different [32–35]. With further advancements of research, more scholars aim to use system dynamics, artificial intelligence, and integrated technology methods for dynamic simulation and scenario prediction [36,37].

At present, research on the relationship between urbanization and eco-environment is in its ascendancy [38]. It is focused mainly on using the coupling degree and CCD to measure the mutual influence and coordinated development between the two components [39,40]. The CCD can be used to evaluate the coordination degree of urbanization and eco-environment coupling, and the Tapio decoupling model can express the impact of urbanization on eco-environment. However, the coupling degree and the CCD are unable to reflect the qualitative and quantitative influence degree between subsystems at different development stages in the coupling system. The symbiosis degree model is a dynamic mathematical equation used to express the mutual symbiosis of two species population. It can not only reflect the interaction mode of two symbiotic units, but also reflect the interaction intensity between them. To this end, this study introduces symbiosis theory, which is based on the coupling coordination degree and the Tapio decoupling model. This study aims to understand the interaction mode and intensity between urbanization and eco-environment at different stages of development. The theory originated from ecology and was put forward by Derby in 1879 [41]. It claims that different species depend on a certain material connection to coexist. Thus, the symbiosis degree describes the degree of symbiosis between units, thus reflecting the development and operating law of the entire symbiotic system [42]. Moreover, it has achieved good development in the ecological field [43,44]. For example, Delaux et al. studied the effects of microbial symbiosis on plant evolution [45]. Furthermore, Griesmann et al. were able to explain the effect of symbiosis between plants and nitrogen-fixing bacteria on the global nitrogen cycle from the perspective of genetics [46]. Gutjahr et al. explored the effects of environment and symbiotic bacteria on rice growth [47]. With its continuous development, symbiosis theory gradually began to be applied to anthropology, economics, sociology, and various other fields. Based on this theory, Wang et al. studied the synergistic effect of the water-energy-food relationship in the Beijing-Tianjin-Hebei region [48].

Based on symbiosis theory, there are three symbiotic elements between urbanization and eco-environment. The first symbiotic unit, urbanization and eco-environment may form a symbiont or symbiotic relationship between the basic energy production and exchange units. The second symbiosis mode or relationship is the way and form of interaction between urbanization and the eco-environment, such as parasitic symbiosis and mutualism. The third symbiotic environment, the development exogenous conditions of urbanization and eco-environment symbiotic mode is the harmonious coexistence of man and nature. Furthermore, urbanization and the eco-environment coincide with the principle of compatibility of quality parameters. The internal relationship between the two symbiotic units shows that their quality parameters can be expressed mutually. In addition, the SHUE satisfies the principle of symbiotic energy generation. Environmental protection enterprises within the production process can improve the quality of the eco-environment, while also promoting social development, and thus improving the level of urbanization. Based on the above analysis, there are mutual influences, restriction, common development and mutual symbiosis between urbanization and the eco-environment, which conforms to the symbiosis theory hypothesis. This study extends the scope of symbiosis theory to urban geography and puts forth the hypothesis of symbiosis between urbanization and eco-environment. The symbiosis degree is used to explore the type and size of mutual influence between the eco-environment and urbanization.

Under the national strategic background of the coordinated development of Beijing-Tianjin-Hebei, the construction of the Xiong'an New Area and the urbanization construction in the node cities in Hebei Province as an important area to undertake the non-capital functions of Beijing, have their particularity and are also the main area of new urbanization in Beijing-Tianjin-Hebei. As a result, the urban system planning of Hebei Province (2016–2030) suggests that the urbanization rate of permanent residents will reach 70% by 2030 in Hebei Province, China. With accelerated urbanization after the proposal of the Beijing-Tianjin-Hebei integration strategy in 2014, the urbanization level of Hebei Province has been significantly accelerated. However, it has also put extensive pressure on water resources, land resources, and the eco-environment in Hebei Province, partially restricting the development of the social economy and urbanization. Faced with eco-environment pressure, it is crucial to understand how to adequately promote the coordinated development of urbanization and eco-environment. Present research has focused on the quantitative measurement of the coupling relationship in Beijing-Tianjin-Hebei urban agglomeration and the discrimination of coordinated development types [49–51]. Some scholars have examined the relationship between urbanization and eco-environment in Hebei Province, China [52–54]. However, very few studies have systematically and quantitatively explored the interactive relationship between urbanization and eco-environment in this province.

Therefore, the coordinated development of urbanization and the eco-environment needs further examination. To relatively comprehensively reveal the interactive relationship between urbanization and the eco-environment in Hebei Province, starting from Hebei Province as a whole, this study proposes the symbiosis hypothesis of urbanization and the eco-environment. It integrates various mathematical models to conduct a quantitative study on the interaction relationship between them in two dimensions, coupling and decoupling, to realize the whole process analysis of coupling quantitative measurement, coupling type identification, decoupling path exploration and symbiosis hypothesis verification. These results should provide references and suggestions for promoting the coordinated and healthy development of urbanization and eco-environment in Hebei Province. Furthermore, they will enrich the research field concentrated on the interactive stress relationship between urbanization and the eco-environment.

2. Materials and Methods

2.1. Overview of the Study Area

Hebei Province is in the North China Plain, between 36°0′–42°40′ N and 113°27′–119°50′ E. It surrounds the Chinese capital Beijing and is adjacent to Tianjin and the Bohai Sea. Its terrain is high in the northwest and low in the southeast, tilted from northwest to southeast (Figure 1). Hebei Province is the only one to have plateaus, mountains, hills, plains, lakes, and seashore. In 2019, the province had a gross national product of 35.145 billion Yuan. Its total resident population was 7.447 million, of which 43.77 million were urban residents, with an urbanization rate of 58.8%. With accelerated urbanization, Hebei Province promotes economic and social development. However, it is also facing environmental issues such as air pollution, water quality decline, land resources shortage and eco-environment pattern imbalance. All these issues restrict urbanization. Simultaneously, a low level of urbanization causes a rural life pollution problem, restricting sustainable development and the improvement of eco-environment quality in Hebei Province. As the main field and eco-environment support area of the national strategy of the Beijing-Tianjin-Hebei integration and the construction of Xiong'an New Area, the functional orientation of cities in Hebei Province has its individuality. Therefore, it is crucial to ensure and improve the coordinated level of urbanization and eco-environment in Hebei Province and promote the coordinated development of the Beijing-Tianjin-Hebei urban agglomeration as a whole.

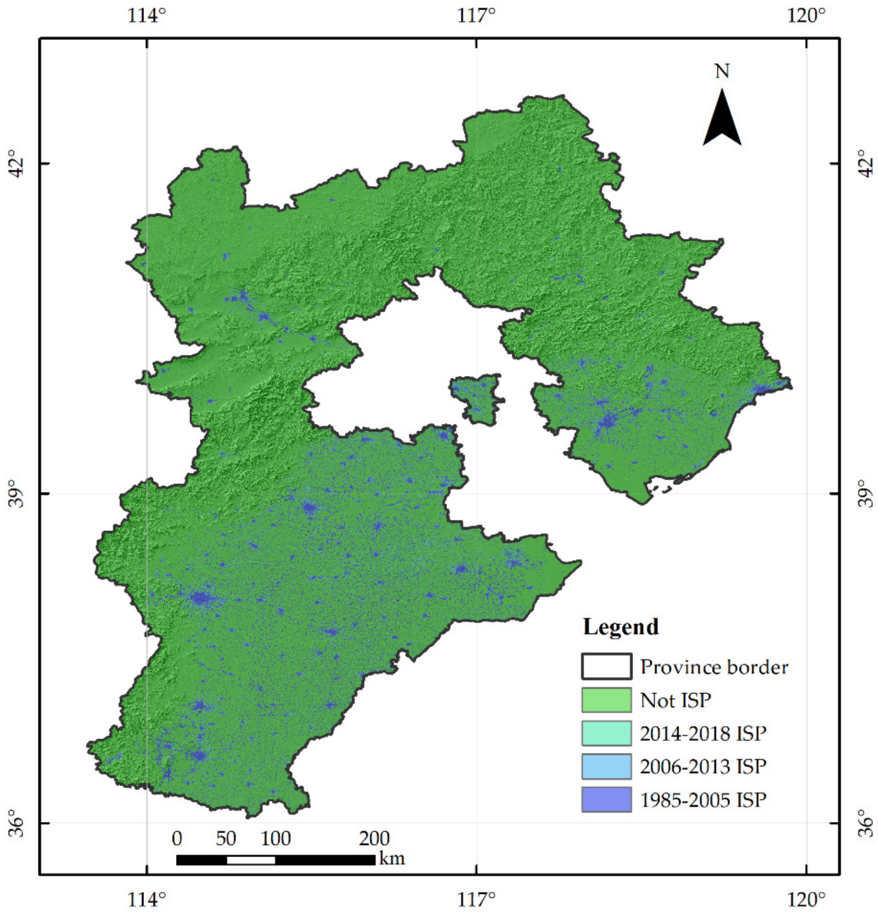

Figure 1. Distribution of ISP in Hebei Province, China.

2.2. Data Source

To examine the relationship between urbanization and the eco-environment, this study uses data for the Hebei Province from 1985 to 2019. Combined with a comprehensive evaluation index system of urbanization and eco-environment, the data source involves two aspects. The first is statistical data, obtained from the China Statistical Yearbook (1986–2020) [55], China Urban Statistical Yearbook (1986–2020) [56], Hebei Statistical Yearbook (2020) [57], Hebei Economic Yearbook (1986–2019) [58], and Hebei Water Resources Bulletin (http://slt.hebei.gov.cn/, accessed on 20 April 2022). The second source is remote sensing monitoring data. Impervious Surface Percent (ISP) is selected as the comprehensive evaluation index to reflect the eco-environment pressure. The ISP data are gathered from the Earth System Research Center of Tsinghua University (Finer Resolution Observation and Monitoring -Global Land Cover). The resolution is 30 m and is interpreted by the Landsat image (TM/ETM+/OLI) provided by the Google Earth Engine platform, with an overall accuracy higher than 90% [59].

2.3. Research Method

Based on the symbiosis hypothesis, this study first divides the urbanization and eco-environment by using the comprehensive evaluation method and the improved 'Northam Curve'. After, the distance coordination coupling model, the Tapio decoupling model and the symbiosis model are used to quantitatively measure the relationship between urbanization and eco-environment from two dimensions: coupling and decoupling. The study analyses its dynamic evolution characteristics. In accordance with the research results, suggestions are put forward, and the basic research ideas are shown in Figure 2.

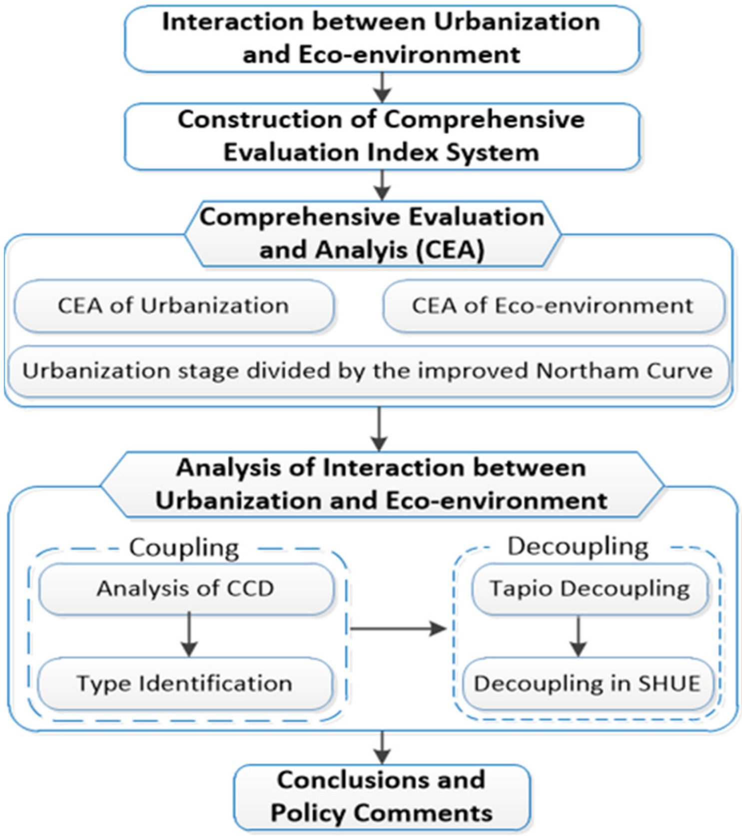

Figure 2. Analysis Framework of Interaction between Urbanization and Eco-environment.

2.3.1. A Comprehensive Evaluation Method of Urbanization and Eco-Environment

1. Construction of a Comprehensive Evaluation Index System.

Urbanization and eco-environment are two relatively complex subsystems within social development. Therefore, it is necessary to establish a reasonable evaluation index system for their analysis. Combined with existing research [60,61] and following the principles of scientific nature, data availability, representativeness and systematic processes, ten representative indicators were selected from four dimensions, those of population, economy, society, and spatial urbanization. Furthermore, to construct a comprehensive evaluation index system of eco-environment, thirteen specific indicators were selected from four aspects, those of resource elements, ecological elements, ecological pressure and ecological response. In addition, the urbanization process increases the impervious surface percent (ISP) [62], thus impacting the urban eco-environment. This study introduces ISP as the eco-environment pressure evaluation index. The comprehensive evaluation index system was constructed as shown in Table 1.

Table 1. Index System and Weight of Urbanization and Eco-environment.

System	First Grade Indicator	Weight Calculation			Basic Grade Indicator	Index Calculation		
		EM	AHP	CW		EM	AHP	CW
Urbanization	Population	0.162	0.123	0.142	Urban Population Proportion	0.376	0.552	0.463
					Natural Growth Rate of Population	0.624	0.448	0.537
	Economy	0.397	0.388	0.394	Gross Regional Product Per Capita	0.305	0.470	0.419
					The Proportion of Second and Third Industries in GDP	0.070	0.280	0.154
					The Proportion of Fiscal Revenue in Regional GDP	0.162	0.114	0.150
					The Total Investment in Fixed Assets of the whole Society	0.463	0.136	0.277
	Space	0.059	0.101	0.077	Urban Built-up Area Per Capita	1	1	1
	Society	0.382	0.388	0.387	Disposable Urban Income Per Capita	0.298	0.550	0.418
					Number of Hospital Beds Per 10,000 People	0.341	0.210	0.277
					Total Retail Sales of Consumer Goods	0.361	0.240	0.305
Eco-environment	Resource Element	0.220	0.170	0.198	Total Available Water Resource Per Capita (+)	0.381	0.550	0.484
					Arable Land Per Capita (+)	0.223	0.330	0.286
					Total Food Production Per Capita (+)	0.396	0.120	0.230
	Ecological Element	0.276	0.460	0.365	Green Coverage Rate of Built District (+)	0.222	0.370	0.292
					Green Area Per Capita (+)	0.466	0.300	0.381
					Percentage of Forest Cover (+)	0.312	0.330	0.327
	Ecological Pressure	0.250	0.270	0.266	Industrial Wastewater Discharge Per Capita (-)	0.224	0.250	0.242
					SO_2 Emissions Per Capita (-)	0.363	0.480	0.427
					Industrial Waste Production Per Capita (-)	0.205	0.070	0.123
					ISP (-)	0.208	0.200	0.208
	Ecological Response	0.254	0.110	0.171	Comprehensive Utilization Rate of Industrial Solid Waste (+)	0.192	0.360	0.272
					Urban Sewage Treatment Rate (+)	0.428	0.460	0.458
					Hazard-free treatment ratio for home refuse (+)	0.380	0.180	0.270

Note that '+' represents the positive indicator, while '-' represents the negative indicator. EM, AHP and CW represent the entropy method, analytic hierarchy process and the comprehensive weight, respectively.

2. Data Standardization and the Weighting Method.

To eliminate the influence of the dimensional difference of each index, the range standardization method was used to reduce the interference of random factors [63]. Considering that there are positive and negative indicators in the eco-environment index system, different standardized calculation formulas were adopted, as shown in Formula (1)

$$A_{ij} = \begin{cases} \frac{X_{ij}-\min(X_{ij})}{\max(X_{ij})-\min(X_{ij})}, & X_{ij} \ is \ positive \ \ indicator \\ \frac{\max(X_{ij})-X_{ij}}{\max(X_{ij})-\min(X_{ij})}, & X_{ij} \ is \ negative \ indicator \end{cases} \quad (1)$$

where i represents the indicator serial number, and j denotes the year. Furthermore, X_{ij} represents the actual value, while $\max(X_{ij})$ and $\min(X_{ij})$ denote the maximum and minimum value of indicator i. After standardization, the greater the value of all the indicators is the better.

This study used a combination of a subjective and objective weight determination methods to obtain relatively accurate results. The former, the subjective weight was determined by an analytic hierarchy process (AHP), while the indexes in the comprehensive evaluation index system were scored according to existing literature [61,64]. On the other hand, the objective weight was determined by the entropy method (EM). To reduce the deviation, the minimum information entropy principle was used to calculate the comprehensive weight (CW), as shown in Formula (2) [65], Values for w_{1i}, w_{2i} were calculated by the entropy method and the analytic hierarchy process, respectively. The process of obtaining the index weight of urbanization and eco-environment comprehensive is shown in Table 1.

$$w_i = \frac{(w_{1i} \times w_{2i})^{\frac{1}{2}}}{\sum\limits_{i=1}^{n} (w_{1i} \times w_{2i})^{\frac{1}{2}}} \quad (2)$$

3. Comprehensive Evaluation Calculation Method.

Based on the comprehensive weight of each indicator, the study used the linear weighting method to calculate the results of population, economy, society and spatial urbanization. This method was also employed to calculate the evaluation index values of resource elements, ecological elements, ecological pressure, and ecological response subsystems. After these were determined, the results of urbanization and eco-environment system were obtained according to the weight of the basic grade indicator. The formulas for this are provided in Equations (3) and (4).

$$f(x) = \sum_{i=1}^{n} w_i \times x_i, \quad g(y) = \sum_{j=1}^{m} w_j \times y_j \tag{3}$$

$$F(x) = \sum_{i=1}^{n} W_i \times f(x), \quad G(y) = \sum_{j=1}^{m} W_j \times g(y) \tag{4}$$

where $f(x)$ and $g(y)$ denote the value of urbanization and eco-environment subsystem, while $F(x)$ and $G(y)$ represent the integrated value of urbanization and eco-environment system. Next, x_i and y_j denote the standardized value of the urbanization and eco-environment basic grade indicator, while w_i, w_j represent the CW of this indicator. Finally, W_i and W_j denote the CW of urbanization and eco-environment subsystem.

2.3.2. The Improved Northam Curve

In 1975, Northam used a logistic equation to conduct a regression analysis of the urbanization level of developed countries. He found that the level of urbanization satisfied the logistic equation and the proposed 'Northam Curve', namely, the urbanization process presented a flattened inverted S-shaped curve. Instead of urbanization rate, this study used the urbanization comprehensive evaluation index to characterize the level of urbanization. In addition, it also used the multivariate regression analysis method to quantitatively analyse the change law of urban level with time. The development stage of urbanization was divided in accordance with these calculations. The formula for this is shown in Equation (5):

$$y_{(t)} = \frac{y_{\max}}{1 + \left({y_{\max}}/{y_0} - 1\right)e^{-rt}} \tag{5}$$

where y_0 represents the minimum level of the urbanization.

2.3.3. Distance Coordination Coupling Degree Model

The CCD model quantitatively evaluates the coordination degree of the interaction between the urbanization system and the eco-environment system. It can detail the problems within the development process. This paper employed the distance coordination coupling degree model to explore the degree of coordinated development of the urbanization and eco-environment system. Based on the CCD calculation, the Euclidean distance formula was introduced and measures the distance between the actual state and the ideal state of the system, and it is the deviation between the actual value and the ideal value of the evaluation variable. When the system is in ideal coordination, the two systems pull towards and are in the state of coordinated development. The symbols x_{1t}, x'_{1t}, x_{2t}, x'_{2t} were used to represent the actual and ideal values of the t^{th} year development degree of the urbanization system and eco-environment system. Furthermore, $(x'_{1t}, x'_{2t})^T$ is equal to $(x_{2t}, x_{1t})^T$. Afterwards, it is necessary to construct Equation (6) [66]:

$$c_t = \left(\sqrt{1 - \sqrt{\frac{\sum_{i=1}^{2} \left(x_{it} - x'_{it}\right)^2}{\sum_{i=1}^{2} S_i^2}}} \right)^k \tag{6}$$

Assuming that the urbanization system is as important as the eco-environment one, S_1, S_2 are taken to be 1. Furthermore, k is taken as 2 and represents the adjustment coefficient.

The distance coordination degree between urbanization and eco-environment system may be expressed by Equation (7):

$$c_t = \left(\sqrt{1 - \sqrt{\frac{\left(x_{1t} - x'_{1t}\right)^2 + \left(x_{2t} - x'_{2t}\right)^2}{2}}}\right)^2 = 1 - |x_{1t} - x_{2t}| \tag{7}$$

where c_t represents the coordination degree of the system in the t^{th} year. The CCD of the system in the t^{th} year may be calculated by Equation (8). CCD reflects the coordinated development level of the system.

$$d_t = D(x_t, c_t) = \sqrt{x_t c_t} \tag{8}$$

In the above formula, d_t denotes the CCD of the system in the t year. This study suggests that the higher its value, the better level of the coordinated development of the system.

Previous research [67,68] has divided the coordinated development of urbanization and eco-environment into three categories: coordinated development, transition, and the imbalance category (Table 2). According to specific values, the transition category is further divided into the category of barely coordinated development and the category of endangered imbalance. In total, the coordinated development of urbanization and eco-environment has four subcategories. Based on the difference between development level of urbanization and eco-environment and the actual situation, the coordinated development of urbanization and eco-environment was further divided into 12 basic types.

Table 2. Classification Criteria for Coordinated Development of Urbanization and Eco-environment.

Category	CCD	Subcategory	Comparison between $F(x)$ and $G(y)$	Basic Category
Coordinated Development	0.60~1.00	Coordinated Development (IV)	$F(x) - G(y) > 0.1$	Eco-environment Lag Type (IV-1)
			$\lvert F(x) - G(y)\rvert \leq 0.1$	Synchronization of Urbanization and Eco-environment Type (IV-2)
			$G(y) - F(x) > 0.1$	Urbanization Lag Type (IV-3)
Transition	0.50~0.59	Barely Coordinated Development (III)	$F(x) - G(y) > 0.1$	Eco-environment Lag Type (III-1)
			$\lvert F(x) - G(y)\rvert \leq 0.1$	Synchronization of Urbanization and Eco-environment Type (III-2)
			$G(y) - F(x) > 0.1$	Urbanization Lag Type (III-3)
	0.40~0.49	Endangered Imbalance (II)	$F(x) - G(y) > 0.1$	Eco-environment Lag Type (II-1)
			$\lvert F(x) - G(y)\rvert \leq 0.1$	Synchronization of Urbanization and Eco-environment Type (II-2)
			$G(y) - F(x) > 0.1$	Urbanization Lag Type (II-3)
Imbalance	0.00~0.39	Imbalance (I)	$F(x) - G(y) > 0.1$	Eco-environment Lag Type (I-1)
			$\lvert F(x) - G(y)\rvert \leq 0.1$	Co-dame of Urbanization and Eco-environment Type (I-2)
			$G(y) - F(x) > 0.1$	Urbanization Lag Type (I-3)

2.3.4. Tapio Decoupling Model

Decoupling comes from the field of physics, meaning that the initial relationship between two or more physical quantities is either reduced or no longer exists. The Organization for Economic Cooperation and Development (OECD) introduced the Tapio decoupling model into agricultural policy research. Shortly afterwards, resource and eco-environmental scholars used decoupling to describe the relationship between economic growth and eco-environmental pollution. At present, researchers have used the Tapio decoupling model to study the interaction between aforementioned factors. Guo et al. used it to examine the relationship between urbanization and resource environment in Beijing [69]. Furthermore, Wang et al. used the same model to analyse the decoupling elasticity between carbon emissions and economic growth [70]. Thus, to explore the complex relationship between urbanization and eco-environment at each coordinated development stage, this study employed the Tapio decoupling model and distance CCD model. The decoupling index of year t, (DI_t) is calculated by the following formula [71]:

$$DI_t = \frac{(E_t - E_{t-1})/E_{t-1}}{(U_t - U_{t-1})/U_{t-1}} \tag{9}$$

where E_t and E_{t-1} represent the integrated value of the eco-environment in t and $t-1$ year, while U_t and U_{t-1} denote the integrated values of urbanization in t and $t-1$ year.

The study obtained the decoupling index through the positive and negative growth rates of the eco-environment index and urbanization index. According to the critical values of 0, 0.8, 1.2, the decoupling types were divided into eight types: recession decoupling, strong decoupling, weak decoupling, expansion connection, recession connection, negative expansion decoupling, negative strong decoupling, negative weak decoupling. All of these are shown in Table 3.

Table 3. Classification Criteria for Decoupling Types.

Status		$\triangle E/E$	$\triangle U/U$	DI
Decoupling	Recession Decoupling	-	-	$DI \geq 1.2$
	Strong Decoupling	-	+	$DI < 0$
	Weak Decoupling	+	+	$0 \leq DI < 0.8$
Connection	Expansion Connection	+	+	$0.8 \leq DI < 1.2$
	Recession Connection	-	-	$0.8 \leq DI < 1.2$
Negative Decoupling	Negative Expansion Decoupling	+	+	$DI \geq 1.2$
	Negative Strong Decoupling	+	-	$DI < 0$
	Negative Weak Decoupling	-	-	$0 \leq DI < 0.8$

$\triangle E/E$ and $\triangle U/U$ respectively represent the change rate of eco-environment and urbanization in t year relative to $t-1$ year. + indicates positive value and - indicates negative value.

2.3.5. The Symbiosis Hypothesis of Urbanization and Eco-Environment

A correlation between urbanization and the eco-environment has been proven by scholars [72]. Accordingly, this relationship may be studied by establishing a mathematical model. This study used the regression model to describe this quantitative relationship. The model itself lays the foundation for the construction of symbiosis model. The mathematical model was as follows:

$$x = 2.07 - 13.316y + 28.172y^2 - 16.803y^3 \quad Adj.R^2 = 0.937 \tag{10}$$

$$y = 0.382 - 0.45x + 2.419x^2 - 1.666x^3 \quad Adj.R^2 = 0.895 \tag{11}$$

where in Formulas (10) and (11), x denotes the level of the urbanization system, while y represent the development level of the eco-environment system.

The symbiosis degree model reflects the degree of correlation between two symbiotic units or systems. Using this degree may reveal the independence between the urbanization and eco-environment system. It is conducive to depicting the action and reaction between the urbanization and eco-environment system. Thus, this study used the comprehensive level of urbanization to represent the main parameters of the urbanization system. It also used the comprehensive level of eco-environment to represent the main parameters of the urbanization system. Then, the symbiosis degree of the urbanization system and eco-environment system may be calculated by the following formula [73–75]:

$$\delta_{xy} = \frac{dx/x}{dy/y} = \frac{dx}{dy} \cdot \frac{y}{x} \tag{12}$$

$$\delta_{yx} = \frac{dy/y}{dx/x} = \frac{dy}{dx} \cdot \frac{x}{y} \quad (13)$$

where δ_{xy} represent the symbiosis degree of the urbanization system to the eco-environment system. In other words, it denotes the change that the main parameters of the eco-environment system cause to the main parameters of the urbanization system. Moreover, it reflects the contribution of the eco-environment system symbiosis unit to the urbanization system symbiosis unit. Next, δ_{yx} denotes the symbiosis degree of the eco-environment system to the urbanization system. In other words, it represents the relative change that the main parameters of the urbanization system cause within the eco-environment system. This notion also reflects the contribution of the urbanization system symbiosis unit to the eco-environment system symbiosis unit.

Taking zero as the critical value, the symbiosis mode may be divided into four categories: parasitic symbiosis, partial symbiosis, asymmetric mutualism, and symmetric mutualism (Table 4).

Table 4. Classification Criteria for Symbiosis Mode.

Symbiosis Mode	δ_{xy}	δ_{yx}	$\delta_{xy} \cdot \delta_{yx}$	Interpretative Statement
Parasitic Symbiosis	-	+	<0	Urbanization Promotes Eco-environment; Eco-environment Suppresses Urbanization.
	+	-	<0	Urbanization Suppresses Eco-environment, Eco-environment Promotes Urbanization.
Partial Symbiosis	0	+	0	Urbanization Promotes Eco-environment; The Influence of Eco-environment on Urbanization is offset.
	+	0	0	Eco-environment Promotes Urbanization; The influence of Urbanization on Eco-environment is offset
Asymmetric Mutualism	+	$> \delta_{xy}$	>0	Urbanization Promotes the other more than Eco-environment
	$> \delta_{yx}$	+	>0	Eco-environment Promotes the other more than Urbanization
Symmetric Mutualism	+	$= \delta_{xy}$	>0	Urbanization and Eco-environment Promote Each Other in The Same Degree

Note: + indicates positive value and - indicates negative value.

3. Results and Interpretation

3.1. Comprehensive Evaluation of the Urbanization System and Eco-Environment

3.1.1. Analysis on the Evolution of the Comprehensive Urbanization Level

Based on the comprehensive weight of each index, the comprehensive level index of the urbanization system from 1985 to 2019 was calculated by Formulas (3) and (4). The present study proposes that this index be standardized and transformed into percentage mode rather than urbanization rate. The improved 'Northam curve' is obtained by fitting Equations (5) and (14). The parameter of the fitting equation is in line with expectations, while its adjusted determination coefficient R2 is 0.8291. In sum, the fitness of the improved 'Northam curve' is good. The curve in question obtained by our judgment satisfies the logistic equation. As Figure 3 shows, the curve describes the trend of urbanization with time and presents a flat inverted S-shaped curve. During 1985 to 2019, the overall level of urbanization was low, and tended to rise in Hebei Province. In terms of stages, between 1985 and 2005, the urbanization level was less than 30%, its changes were not evident, and urbanization development was in the initial stage. From 2006 to 2013, the level of urbanization was between 30~70%, indicating that it had increased significantly. Thus, this was a rapid development stage. Rapid urbanization was especially evident around 2008. To some extent, the 2008 Beijing Summer Olympic Games played a role in promoting the urbanization process in Hebei Province. Furthermore, from 2014 to 2019, the level of urbanization was more than 70%, meaning that the development of urbanization was in the mature stage. The change rate of urbanization was gradually slowing down, showing a relatively stable state. According to the above analysis, the urbanization process conformed to the standard S-shaped curve in Hebei Province.

$$x = \frac{100}{1 + 8.9e^{-0.08974 \times (t-1985)}} \quad Adj.R^2 = 0.8291 \quad (14)$$

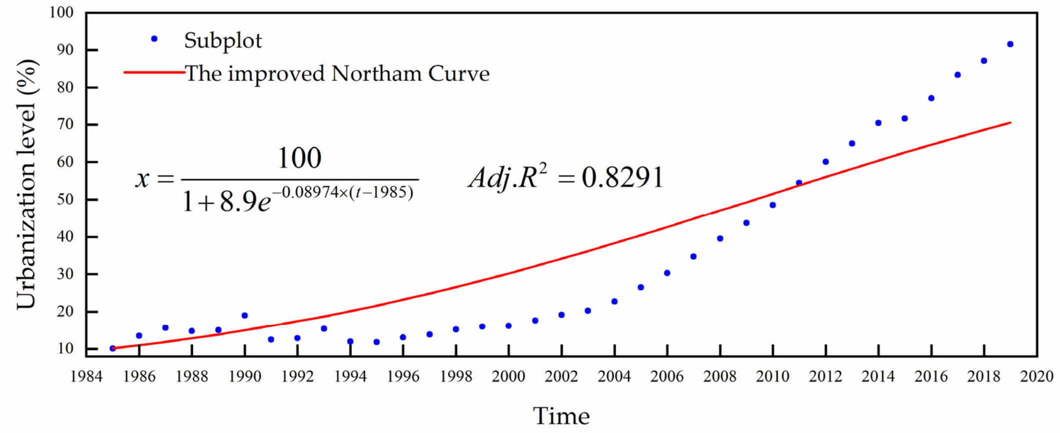

Figure 3. The improved 'Northam curve' of urbanization level from 1985 to 2019 in Hebei Province, China.

3.1.2. Analysis on the Evolution of the Comprehensive Eco-Environment Level

A similar process of urban comprehensive evaluation was used to calculate the comprehensive level index of eco-environment in Hebei Province from 1985 to 2019. The results are provided in Figure 4. The level of eco-environment showed a downward trend from 1985 to 1990. After 1990, it gradually increased, reaching its peak in 1996. However, it showed a downward trend once again until 1998. After this year, the comprehensive level of eco-environment steadily increased. Overall, the comprehensive level of eco-environment exhibited a fluctuating upward trend. Furthermore, the evaluation index of resource element subsystem exhibits large fluctuations in some parts, showing a general downward trend. These results indicate that the resource pressure was gradually increasing, which is consistent with the current water and land shortage in Hebei Province. Moreover, the evaluation index of the ecological pressure subsystem showed an initial decreasing trend, followed by an increase. This fluctuation was due to industrialization, urbanization, and the increase of pollutant emissions and ISP. Namely, all these factors led to the increase of ecological subsystem pressure. Fortunately, with the improvement of industrial emission reduction, consumption reduction and pollutant emission control level, the ecological pressure has been relatively reduced. Therefore, the ecological pressure index gradually increased. The evaluation index of the ecological response subsystem and ecological element subsystem showed a rising trend. It indicated that the increase of eco-environment protection investment, the implementation of pollution control measures and policies and the strengthening of urban green space construction had a positive effect on ecological element subsystems and ecological response subsystems.

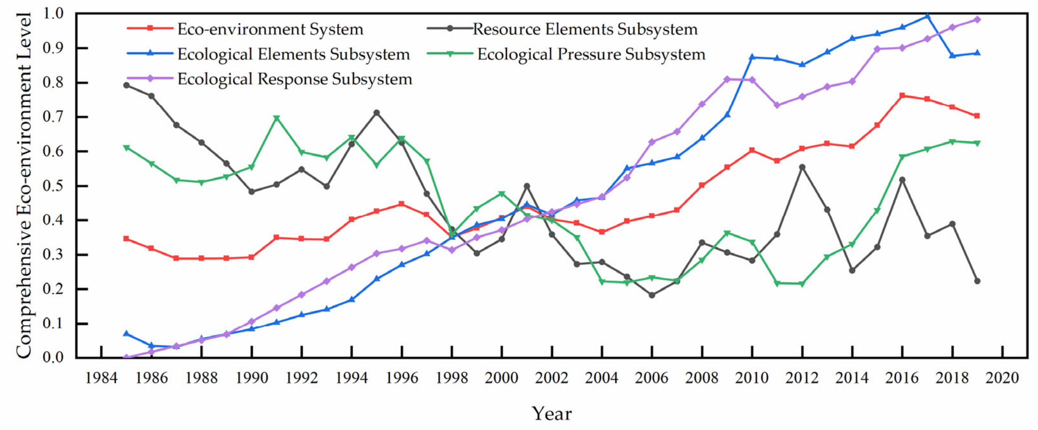

Figure 4. Comprehensive Eco-Environment Level in Hebei Province, China.

3.2. Analysis of Coupling Relationship between Urbanization and Eco-Environment

3.2.1. Analysis of Coupling Coordination Degree Change

The CCD is based on the comprehensive index of urbanization and eco-environment. It was calculated by the distance coordination coupling degree model. The results are provided in Figure 5. In general, the CCD between urbanization and eco-environment increased from 1985 to 2019. In terms of its stage, from 1985 to 2005, urbanization development was in its initial stage, and the development of urbanization is slow, while CCD between urbanization and eco-environment was low. From 2006 to 2013, urbanization development was in the rapid stage, the continuous improvement of urbanization had promoted the improvement of eco-environment to a certain extent, and the CCD rapidly increased. From 2014 to 2019, the development of urbanization was in the mature stage, while the level of urbanization had been further improved, it had a negative impact on eco-environment, and the quality of eco-environment first increased and then decreased, resulting in the same change trend of the CCD. Since 2016, the government has vigorously promoted new urbanization in Hebei Province. The urbanization speed is ahead of eco-environment construction, causing the CCD to decline.

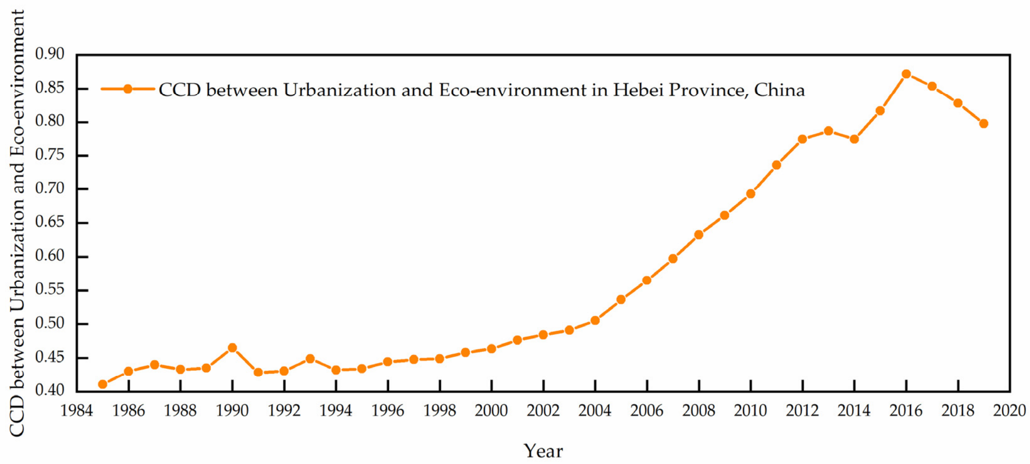

Figure 5. CCD between Urbanization and Eco-environment from 1985 to 2019 in Hebei Province, China.

3.2.2. Type Identification of Coupling Coordination Relation

Overall, the coordination degree between urbanization and the eco-environment in Hebei Province has continuously improved. However, it has been in the lagging stage of urbanization development for a long time (Table 5). Furthermore, the level of urbanization lags behind the level of eco-environment, the coupling coordination type (CCR) is constantly changing. From 1985 to 2003, the urbanization and eco-environment system was in the lagging stage, in the category of endangered imbalance. Between 2004 and 2006, the system was in the lagging stage again, defined this time as barely coordinated development urbanization. From 2007 to 2010, the CCR transited from the synchronous type of urbanization and eco-environment to the coordinated development type of lagging urbanization. Next, between 2011 and 2017, the urbanization and eco-environment system was in the synchronous stage of coordinated development. However, with water, soil, and other shortages, the eco-environment system lagged behind the development of the urbanization system. Finally, in 2018 and 2019, the CCR between urbanization and eco-environment shifted to the lagging type in the category of coordinated development. These changes show that urbanization in Hebei Province has advanced in recent years.

Table 5. CCR between Urbanization and Eco-environment in Hebei Province, China.

Year	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**
CCR	(II-3)	(II-3)	(II-3)	(II-3)	(II-3)	(II-3)	(II-3)	(II-3)
Year	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
CCR	(II-3)	(II-3)	(II-3)	(II-3)	(II-3)	(II-3)	(II-3)	(II-3)
Year	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
CCR	(II-3)	(II-3)	(II-3)	(III-3)	(III-3)	(III-3)	(III-2)	(IV-3)
Year	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
CCR	(IV-3)	(IV-3)	(IV-2)	(IV-2)	(IV-2)	(IV-2)	(IV-2)	(IV-2)
Year	**2017**	**2018**	**2019**					
CCR	(IV-2)	(IV-1)	(IV-1)					

IV-1, IV-2 and IV-3 respectively represent eco-environment lag type, synchronization of urbanization and eco-environment type, urbanization lag type of coordinated development; III-2 and III-3 respectively represent synchronization of urbanization and eco-environment type, urbanization lag type of barely coordinated development; II-3 represents urbanization lag type of endangered imbalance.

3.3. Decoupling Path of Interaction between Urbanization and Eco-Environment

The study calculated and classified the decoupling index of urbanization and eco-environment in Hebei Province from 1985 to 2019. Table 6 illustrates these results. During the research period, the state of index decoupling exhibited six states: strong decoupling, weak decoupling, negative expansion decoupling, expansion connection, negative strong decoupling, and negative weak decoupling. Furthermore, the degree of decoupling showed dynamic changes between strong and weak decoupling. In reference to the degree of decoupling, strong decoupling appeared 14 times, while other decoupling relations were recorded 20 times. The average annual growth rate of urbanization index was 0.074, making it higher than the average annual growth rate of eco-environment index (0.024). This discrepancy indicates that the growth rate of the former index is higher than that of the latter. Furthermore, in reference to the type of decoupling, the urbanization process in Hebei Province belongs to positive urbanization, while the development of urbanization and the implementation of corresponding policies have contributed positive forces to the sound development of eco-environment, and its eco-environment is gradually improved. In the initial and rapid development stages, the CCD between urbanization and eco-environment exhibited an overall upward trend, showing a positive urbanization in the decoupling type and indicating that the level of urbanization has significantly improved. Simultaneously, the level of eco-environment was also steadily improved at this stage. However, in the mature stage of urbanization, the comprehensive level of urbanization increases, while the comprehensive level of eco-environment decreases. Moreover, during this stage, the coupling and coordination degree of urbanization and eco-environment first increased and then decreased. The coupling type changed from a synchronous type to a lagging type during this stage. The number of strong decoupling was significantly higher than that of other decoupling degrees, exhibiting negative urbanization.

Table 6. Decoupling Index of Urbanization and Eco-environment in Hebei Province, China.

Year	△*E*/*E*	△*U*/*U*	*DI*	Status	Year	△*E*/*E*	△*U*/*U*	*DI*	Status
1986	−0.0815	0.3394	−0.2403	Strong Decoupling	2003	−0.0280	0.0586	−0.4770	Strong Decoupling
1987	−0.0891	0.1589	−0.5608	Strong Decoupling	2004	−0.0679	0.1178	−0.5764	Strong Decoupling
1988	−0.0008	−0.0582	0.0140	Negative Weak Decoupling	2005	0.0859	0.1678	0.5117	Weak Decoupling
1989	0.0016	0.0177	0.0930	Weak Decoupling	2006	0.0414	0.1437	0.2883	Weak Decoupling
1990	0.0109	0.2635	0.0414	Weak Decoupling	2007	0.0416	0.1456	0.2859	Weak Decoupling
1991	0.1927	−0.3433	−0.5614	Negative Strong Decoupling	2008	0.1670	0.1365	1.2229	Negative Expansion Decoupling
1992	−0.0103	0.0281	−0.3678	Strong Decoupling	2009	0.1042	0.1061	0.9825	Expansion Connection
1993	−0.0037	0.1991	−0.0186	Strong Decoupling	2010	0.0893	0.1115	0.8008	Expansion Connection
1994	0.1658	−0.2238	−0.7409	Negative Strong Decoupling	2011	−0.0513	0.1205	−0.4253	Strong Decoupling
1995	0.0637	−0.0111	−5.7199	Negative Strong Decoupling	2012	0.0634	0.1046	0.6061	Weak Decoupling
1996	0.0482	0.1049	0.4600	Weak Decoupling	2013	0.0243	0.0812	0.2988	Weak Decoupling
1997	−0.0695	0.0631	−1.1015	Strong Decoupling	2014	−0.0139	0.0838	−0.1659	Strong Decoupling
1998	−0.1567	0.0981	−1.5976	Strong Decoupling	2015	0.0997	0.0176	5.6705	Negative Expansion Decoupling
1999	0.0743	0.0502	1.4798	Negative Expansion Decoupling	2016	0.1290	0.0762	1.6922	Negative Expansion Decoupling
2000	0.0794	0.0130	6.1133	Negative Expansion Decoupling	2017	−0.0133	0.0809	−0.1642	Strong Decoupling
2001	0.0845	0.0898	0.9404	Expansion Connection	2018	−0.0312	0.0462	−0.6759	Strong Decoupling
2002	−0.0876	0.0877	−0.9988	Strong Decoupling	2019	−0.0372	0.0500	−0.7443	Strong Decoupling

3.4. Symbiosis Degree Analysis of Interaction between Urbanization and Eco-Environment

3.4.1. Analysis of Symbiosis Degree between Urbanization and Eco-Environment

As shown in Figure 6, the symbiosis degree model calculates the symbiosis degree of urbanization and eco-environment. The symbiosis degree of urbanization to eco-environment exhibits great fluctuations and shows an overall upward trend. Except for the negative values from 1986 to 1990, the symbiosis degree of urbanization to eco-environment was greater than zero. This indicates that the contribution of eco-environment to urbanization was negative, urbanization was inhibited by the eco-environment during the early period of urbanization, and after 1991, the contribution of eco-environment to urbanization was positive. Nevertheless, the eco-environment has a promoting role in urbanization. The symbiosis degree of eco-environment to urbanization shows a trend of an initial slow rise followed by a rapid decline. During the initial and rapid development stages, the symbiosis degree of eco-environment to urbanization exhibited a slow upward trend. Furthermore, this degree is mostly positive, indicating that the urbanization development promotes the improvement of the eco-environment level. During the mature stage of urbanization, the symbiotic degree shows a significant downward trend, specifically from 0.1795 in 2014 to −0.8194 in 2019. In 2016, the symbiosis degree of eco-environment to urbanization began to become negative, and the contribution of urbanization to eco-environment was negative. This shows that urbanization development between 2016 and 2019 focused on the eco-environment.

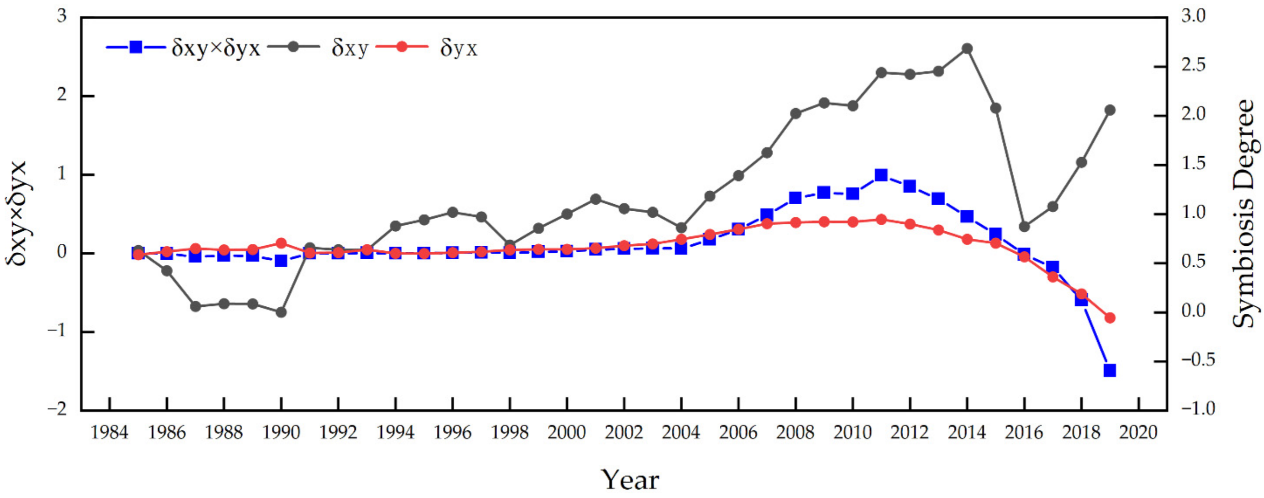

Figure 6. Symbiosis Degree between Urbanization and Eco-environment from 1985 to 2019 in Hebei Province, China.

3.4.2. Pattern Recognition of Symbiosis between Urbanization and Eco-Environment

The symbiotic mode of urbanization and eco-environment in Hebei Province from 1985 to 2019 was based on the division standard of the symbiotic mode (Table 4), which are either asymmetric mutualism or parasitic mode (Table 7). In terms of the number of occurrences, the asymmetric mutual benefit symbiosis mode (24 times) was more present than the parasitic mode (11 times). Overall, urbanization and the eco-environment appear to promote each other, which is consistent with the results obtained by Wan et al. [76]. For the parasitic mode that occurred during the study period, the main performance was that the eco-environment parasitized over urbanization from 1986 to 1990, while urbanization development parasitizes over the eco-environment from 2016 to 2019. Together with the coupling, decoupling, and symbiosis analyses, during the initial stage and the rapid development stage, the coupling and coordination degree of urbanization and eco-environment exhibited an upward trend. Namely, it shows positive urbanization in the decoupling type, and mutually beneficial symbiosis in the symbiosis mode. Overall, both the urbanization level and eco-environment level have significantly improved. Within the mature stage, the CCD first increased and then decreased. The coupling type belongs to the synchronous type of coordinated development and coordinated development of the eco-environment lag type. Within the decoupling type, its type shows negative urbanization. Between 2016 and 2019, the symbiotic mode exhibited the parasitic mode. In other words, urbanization development parasitizes over the eco-environment and puts great strain on it. Finally, the coupling and coordinated development type changed from coordinated development to coordinated development of the eco-environment lag type category.

Table 7. Symbiosis Mode between Urbanization and Eco-environment in Hebei Province, China.

Year	δ_{xy}	δ_{yx}	$\delta_{xy} \cdot \delta_{yx}$	Symbiosis Mode	Year	δ_{xy}	δ_{yx}	$\delta_{xy} \cdot \delta_{yx}$	Symbiosis Mode
1985	0.0384	−0.0171	−0.0007	Parasitic	2003	0.5245	0.1212	0.0636	Asymmetric Mutualism
1986	−0.2195	0.0217	−0.0048	Parasitic	2004	0.3271	0.1786	0.0584	Asymmetric Mutualism
1987	−0.6745	0.0617	−0.0416	Parasitic	2005	0.7295	0.2411	0.1759	Asymmetric Mutualism
1988	−0.6391	0.0448	−0.0286	Parasitic	2006	0.9893	0.3079	0.3046	Asymmetric Mutualism
1989	−0.6426	0.0495	−0.0318	Parasitic	2007	1.2812	0.3789	0.4855	Asymmetric Mutualism
1990	−0.7477	0.1307	−0.0977	Parasitic	2008	1.7808	0.3941	0.7018	Asymmetric Mutualism
1991	0.0723	0.0066	0.0005	Asymmetric Mutualism	2009	1.9152	0.4022	0.7702	Asymmetric Mutualism
1992	0.0465	0.0109	0.0005	Asymmetric Mutualism	2010	1.8774	0.4014	0.7536	Asymmetric Mutualism
1993	0.0437	0.0470	0.0020	Asymmetric Mutualism	2011	2.3015	0.4316	0.9933	Asymmetric Mutualism
1994	0.3481	0.0004	0.0001	Asymmetric Mutualism	2012	2.2784	0.3730	0.8498	Asymmetric Mutualism
1995	0.4270	−0.0008	−0.0003	Parasitic	2013	2.3172	0.2986	0.6920	Asymmetric Mutualism
1996	0.5240	0.0105	0.0055	Asymmetric Mutualism	2014	2.6065	0.1795	0.4678	Asymmetric Mutualism
1997	0.4656	0.0203	0.0094	Asymmetric Mutualism	2015	1.8489	0.1304	0.2411	Asymmetric Mutualism
1998	0.1058	0.0437	0.0046	Asymmetric Mutualism	2016	0.3405	−0.0443	−0.0151	Parasitic
1999	0.3208	0.0518	0.0166	Asymmetric Mutualism	2017	0.5977	−0.2998	−0.1792	Parasitic
2000	0.5018	0.0509	0.0256	Asymmetric Mutualism	2018	1.1601	−0.5142	−0.5966	Parasitic
2001	0.6913	0.0668	0.0462	Asymmetric Mutualism	2019	1.8232	−0.8194	−1.4940	Parasitic
2002	0.5693	0.0984	0.0560	Asymmetric Mutualism					

4. Discussion

In recent decades, the study on the two-way relationship between urbanization and eco-environment has never stopped at home and abroad. On the one hand, the impact of urbanization on resources and eco-environment was concerning [77]; on the other hand, the study paid attention to the constraints of land, water, energy, environmental capacity, and ecological security on the urbanization process [18]. Most scholars use mathematical models, such as the coupling coordination degree model, the grey correlation degree model, and the Tapio model, to measure the coupling coordination relationship between urbanization and eco-environment, and identify the types of coupling coordination development. For example, Zhao et al. used the improved environmental Kuznets curve (EKC) model and dynamic coordination coupling degree (CCD) model to discuss the relationship between urbanization and eco-environment in the Yangtze River Delta [73]; Tan et al. analysed the spatiotemporal changes of urbanization and eco-environment coupling types in different regions of Jilin Province by using the coupling coordination degree [78]. Of course, some scholars have discussed the relationship between urbanization and eco-environment from the single dimension of decoupling [39] or the two dimensions of coupling and decoupling [64]. However, at different stages of urbanization, the relationship between urbanization and eco-environment and the extent of their impact on each other have not been clearly answered, and the research on the relationship between urbanization and eco-environment from the two dimensions of coupling and decoupling has not been deep enough. Compared with existing studies, we used the standardized value of urbanization comprehensive evaluation index to replace population urbanization rate to improve the northern curve, which divided the urbanization of Hebei Province into three stages. On this basis, on the one hand, we put forward the hypothesis of symbiosis between urbanization and eco-environment, on the other hand, from the two dimensions of coupling and decoupling, the interaction between urbanization and eco-environment was discussed quantitatively in the whole process. At the same time, using the hypothesis of urbanization and eco-environment symbiosis to decouple, the decoupling method is innovative. To some extent, the study revealed the interaction relationship and the influence degree between urbanization and eco-environment in different stages of urbanization development. The results provided references for the harmonious development of urbanization and eco-environment in Hebei Province, and expanded the research methods and ideas of the relationship between urbanization and eco-environment.

The results indicate that the CCD between urbanization and eco-environment is on the rise in Hebei Province, and the urbanization process is a positive trend. Urbanization and eco-environment are reinforcing each other in Hebei Province. In addition, the eco-environment contributes more to the development of urbanization. However, due to rapid population urbanization and resource shortage, the main cause of the CCD decrease is the decrease of the evaluation index of the resource factor subsystem. The most obvious cause is the substantial decrease of the total available water resources per capita. This indicates that the water resource shortage has become one of the main factors restricting the coordinated development of urbanization and the eco-environment. Therefore, the government should work to optimize the provincial industrial and planting structure, rationally allocate water resources, implement water-saving measures, strengthen the utilization of recycled water, and improve the utilization efficiency of water resources. At the same time, it is necessary to consider the relationship between urbanization speed and urbanization quality in Hebei Province, and it is necessary to clarify the main problems the eco-environment is facing. The government should adhere to the problem and policy guidance by implementing measures from the aspects of water, soil, air, and eco-environmental protection. Furthermore, the eco-environment capacity should be expanded and the carrying capacity should be improved.

This study comprehensively used various models to identify that the shortage of water resources was the main limiting factor affecting the coordinated development of urbanization and eco-environment from the macro level. However, there was no detailed analysis of how water resources factors affect socio-economic factors, population factors and ecological factors, which made it difficult for us to put forward reasonable suggestions. System dynamics takes simulation technology as a means and combines qualitative and quantitative methods to analyse and study the internal feedback mechanism of complex systems, which can be used for the action relationship between the elements of different subsystems. This is also the way for us to explore the action relationship of the elements between urbanization and eco-environment in the next step.

5. Conclusions

Based on 35 years of panel data and a comprehensive evaluation index system, this study quantitatively examined the urbanization process and interaction between urbanization and the eco-environment in Hebei Province, China by employing the distance coordination coupling model, the Tapio decoupling model, and the symbiosis model, and verified the SHUE. The paper realized the whole process analysis of the interaction between urbanization and the eco-environment from two dimensions: coupling and decoupling. The following conclusions were obtained:

(i) The comprehensive evaluation index of urbanization appears to be on the rise in Hebei Province. The improved 'Northam curve' equation satisfied the logistic equation, with the urbanization process presenting an inverted S-shaped curve in the province. Hebei Province has been actively promoting urbanization and has achieved remarkable results. Namely, its comprehensive evaluation index of urbanization has significantly improved. Furthermore, the overall level of the eco-environment also exhibited a fluctuating upward trend in the province. However, after 2016, the comprehensive evaluation index of the eco-environment declined. More specifically, during rapid urbanization, the ownership of per capita resources decreased, reducing the evaluation index of resources and the resource factor subsystem. These changes then further affect the comprehensive evaluation index of the eco-environment system.
(ii) Overall, the CCD of urbanization and eco-environment had an upward trend, with visible phased changes. In the initial stage of urbanization, the CCD was low. Conversely, in the stage of rapid development, the CCD rapidly increased and reached its peak during the mature stage after which it decreased. With respect to coordination type, it shifted from the endangered imbalance type to the coordinated development type during the study period. However, in the mature stage of urbanization, the type of coordination gradually changed from the synchronous type to the lagging type. The level of urbanization was advanced, and the eco-environment pressure was gradually increasing.
(iii) The degree of decoupling between urbanization and the eco-environment was evident in the dynamic changes of six states of strong and weak decoupling, including 14 strong decoupling relationships and 20 other decoupling relationships. During the study period, the urbanization process exhibited a positive type of urbanization, while the eco-environment gradually improved. With respect to the coupling and decoupling process, the level of urbanization significantly improved in the initial and rapid development stage of urbanization. In turn, this led to a steady improvement in the level of the eco-environment, with the positive effect of urbanization was significantly evident. During the mature stage of urbanization, the CCD initially increased and then decreased, with the number of strong decoupling being significantly higher than that of other decoupling degrees. These results point to a negative effect between urbanization and eco-environment.
(iv) The results of this study verified SHUE. Namely, during the study period, the symbiosis mode of urbanization and eco-environment displayed the asymmetric mutualism mode and the parasitic mode. It also presented the fluctuation change of interaction. Furthermore, the number of asymmetric mutualism modes was higher than that of parasitic mode. Thus, the overall mutual contribution between urbanization and the eco-environment was positive, with the two demonstrating mutual promotion and mutualism. However, between 2016 and 2019, the symbiotic mode was parasitic. The development of urbanization placed stress on the eco-environment, which was consistent with the decreased CCD observed between them, the transformation from the coordination type to the lag type, and the increase in strong decoupling.

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