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The Coupling Coordination and Interaction Mechanism of Land Ecological Security and High-Quality Economic Development in the Beijing–Tianjin–Hebei Region

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Abstract: Land ecological security (LES) and high-quality economic development (HED) are mutually influential. China has three world-class urban agglomerations; the Beijing–Tianjin–Hebei (BTH) region is one of them. It is an important platform for participating in international competition and cooperation. To promote regional sustainable development, it is critical to study the coupling coordination and interaction mechanism of LES–HED subsystems over time and space in the BTH region. This study involved the construction of an aggregated index system to obtain a comprehensive understanding of the subsystems, and then investigated the coupling coordination degree (CCD) of the LES–HED subsystems from 2007 to 2018 using a CCD model. Additionally, a panel vector autoregressive (PVAR) model was applied to analyze the interactive mechanism of the LES–HED subsystems. Finally, a model of the degree of relative development was used to classify the types of regional development. The results showed that the CCD of the LES–HED subsystems in the BTH region had significant spatial and temporal differences. The spatial distribution could be characterized as low in the central area and high in the peripheral area, and the evolutionary law of CCD in the system was from lower to higher levels over time. In addition, improvements in LES promoted HED, but the impact of HED on LES was limited. The development patterns within the cities of the study area included three development types, including an slightly lagging type of LES, a slightly lagging type of HED, and a significantly lagging type of HED. Given the spatial variability of the coupled and coordinated development of LES–HED subsystems, it is necessary to implement different development strategies. This study can inform decisions promoting the coordinated development of LES–HED subsystems for sustainable regional development.

Keywords: land ecological security; high-quality economic development; BTH region; CCD model; PVAR model

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1. Introduction

In 2015, the United Nations set out 17 Sustainable Development Goals (SDGs), representing a global compass for humanity to address ecological, economic, and social challenges [1]. China's rapid economic development has also brought ecological security challenges, such as land degradation, soil erosion, environmental pollution, ecological deterioration, etc. [2,3]. Land ecological security (LES) is the basis of regional ecological security. However, because of the continued overuse of land resources in many areas, land ecosystems have become dysfunctional [4–8]. A conflict between LES and economic development has always existed, restricting sustainable regional development. With an increase in the frequency and intensity of climate and weather extremes, the interactions among climate change, ecosystems, and human societies are mainly negative, so humans need to take effective measures to secure a livable and sustainable future for all [9]. Therefore, there is a need to find a sustainable approach that harmonizes the LES–economy nexus.

Rigorous research on the LES–economy nexus is important for enabling sustainable regional development, and the LES–economy nexus has become an attractive research field. Two methods are frequently used in studies on the coupling relationship between LES and economic development: the environmental Kuznets curve (EKC) and the CCD model. The EKC was first proposed to understand the inverse-U-shaped correlation between environmental quality and economic growth [10]. The EKC has been used in several empirical studies to represent the nonlinear relationship that characterizes the relationship between LES and economic development [11–13]. The EKC assumes independence between the economic and environmental systems, ignoring the interactions between the two systems [14]. This gap is bridged by the study of coupling, which refers to the interaction of two or more systems through various pathways, and which has recently been used to inform the measurement of nonlinear interactions between the environment and urbanization [15]. Therefore, the CCD model has recently been applied in most studies to measure the nonlinear interaction between the subsystems of LES and economic development [16–22]. A coupled coordination analysis can fully determine the CCD of LES and economic development, which is important for achieving coordinated development. In the context of high-quality development and the construction of an ecological civilization, the coupling coordination relationships and the interactive mechanisms of LES–HED subsystems require significant emphasis, though the present understanding is still far from adequate. Current research on the coordinated development of both the LES and economic development subsystems has provided inspiration for this study but still has the following shortcomings. Firstly, the 19th National Congress of the Communist Party of China reported that the Chinese economy has transformed from high-speed growth to high-quality development. HED is an essential requirement for adapting to changes in the main conflicts in Chinese society and to maintain sustainable and healthy economic development. Current studies have mostly focused on the coupling coordination of LES and economic growth, rather than the LES–HED subsystems. The indicators used to evaluate economic development frequently ignore the implications and intrinsic needs of HED in favor of focusing on the total growth rate and the structure of the economy. Second, there has been a lack of consideration of the interactive mechanisms of LES–HED subsystems in existing studies, such as the dynamic and causal relationships.

The panel vector autoregressive (PVAR) model was developed by Love and Zicchin [23]. The PVAR model allows investigations of the dynamic response of variables to shocks. It has been extensively used in research on the interaction mechanisms among macroeconomic and financial systems [24], urbanization, and the maritime economy [25] in recent years. However, few studies have explored the interaction mechanisms of the LES–HED subsystems using the PVAR model. This is an urgent current problem requiring a solution, and addressing this represents an innovative feature of the present study.

Therefore, the purpose of this research was to remedy this deficiency and to seek a more accurate understanding of the LES–HED nexus through applying the CCD and PVAR models. This study can contribute to the coherent development of regional LES–HED subsystems. To quantitatively study the coupling coordination and interaction mechanism of LES–HED subsystems over time and space, the Beijing–Tianjin–Hebei (BTH) region was chosen as the study area, using an aggregated indicator system constructed for the period 2007–2018. The integrated levels of LES–HED subsystems were determined using an entropy-weighted method and a technique for order preference, similar to the ideal solution (TOPSIS) model. The CCD model was then applied to investigate the status of coupling coordination in LES–HED subsystems. Additionally, the PVAR model was utilized to investigate the interactive mechanism of the two subsystems. Finally, a model of the degree of relative development was used to classify the types of regional development in order to provide a basis for selecting the paths of sustainable development. In conclusion, we hope that this study will provide theoretical support for sustainable development and a model of ecological economic transformation in China and globally.

The present study was organized as follows. Section 2 describes the materials and methods. Section 3 presents the results and analysis, which mainly include the coupling coordination relationship, the interaction mechanism, and the types of regional development. Section 4 provides the discussion. Section 5 presents the research conclusions and policy recommendations.

2. Materials and Methods

2.1. Study Area

China has three world-class urban agglomerations, and the BTH region is one of them. It is an important platform for participating in international competition and cooperation. The BTH region includes Beijing, Tianjin, and Hebei Province, and includes 13 cities (Figure 1). As of the end of 2018, its overall population made up approximately 8.1% of China, its regional GDP made up about 9.3% of China, and its water resources made up about 0.79% of China [26]. With the rapid socioeconomic development and urbanization, the unbalanced economic structure, the large differences in social security, the lack of water, and land degradation have severely constrained LES and HED in the BTH region. Promoting the coordinated development of HED and LES in the BTH region is the basis for promoting regional synergistic development and building world-class city clusters.

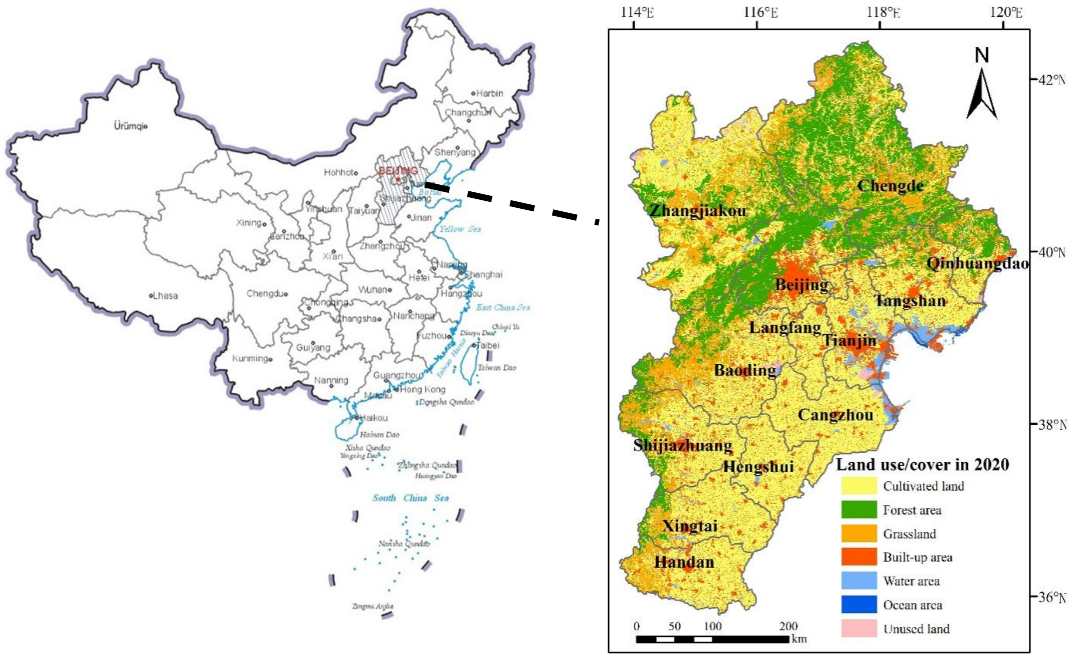


Figure 1. Administrative boundary and patterns of land use of the BTH region.

2.2. Data Sources

The data are from the statistical yearbooks, including the *China Statistical Yearbook* (2008–2019), the *China Urban Statistical Yearbook* (2008–2019), the *Hebei Economic Yearbook* (2008–2019), and the *Hebei Rural Statistical Yearbook* (2008–2019). The data on changes in land use and cover (at a resolution of 1000 m) were obtained from the Resource and Environment Data Cloud Platform of the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (https://www.resdc.cn/DOI/DOI.aspx?DOIID=54, accessed on 6 December 2021). The administrative boundaries were obtained from Standard Map Service Platform, Ministry of Natural Resources of the People's Republic of China (http://bzdt.ch.mnr.gov.cn/, accessed on 6 December 2021).

2.3. Methods

2.3.1. Construction of the Evaluation Index System

The close relationship of LES–HED subsystems is mainly reflected in two aspects [27–29]. First, the impacts of HED on LES are mainly a positive dynamic effect and a negative coercive effect, which are realized through controlling the source, providing an economic basis, and institutional supply. Second, the impact of LES on HED is both positive and negative, which is realized by providing food security, high-quality production factors, and value-added carriers of ecological wealth (Figure 2). The coupling relationship of LES–HED subsystems contains two indispensable parts, including expansion of the amount of development and improvements in the quality of coordination. The government, enterprises, and all sectors of society jointly promote the optimal allocation of the two systems and their internal elements to integrate them into an open and dynamic integrated system. The integrated system develops continuously from low levels to high levels, which is the premise and foundation of regional sustainable development.

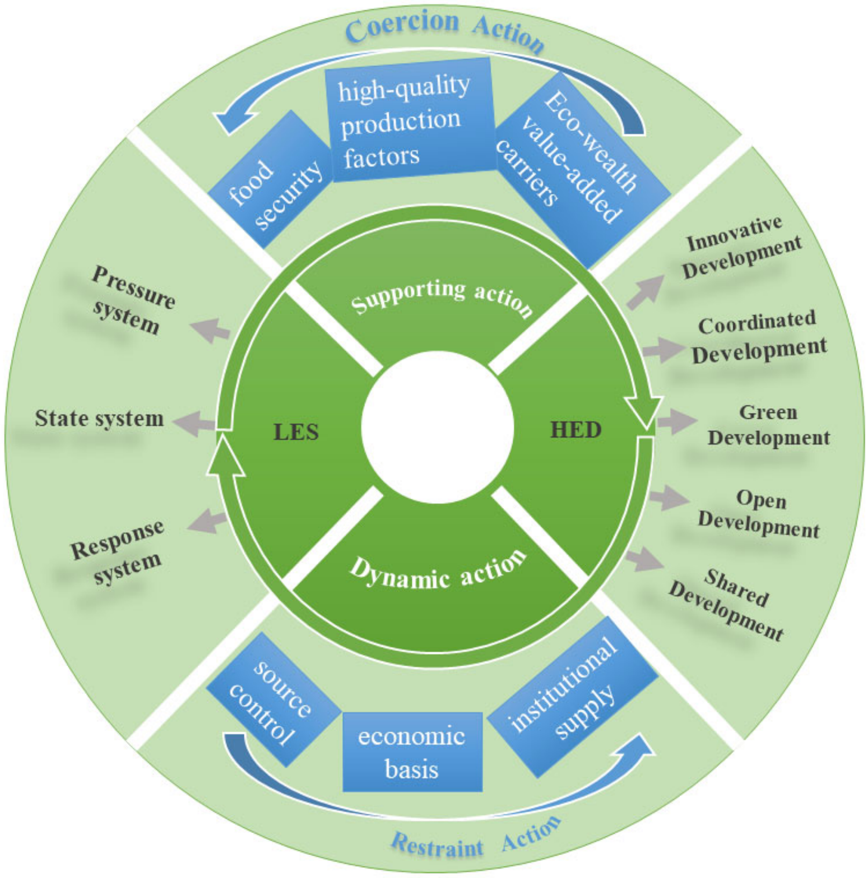


Figure 2. Diagram of the coupling mechanism of LES–HED subsystems.

This study established a mechanism of assessment to assess the LES–HED subsystems. As described in Table 1, in this research, an LES assessment index was constructed, based on the PSR model. Major issues such as deconstruction of the population, industrial transfers, construction of transportation infrastructure, and ecological protection need to be pioneered in the process of collaborative regional development. Therefore, four component layers (population, industry, traffic, and the environment) formed the foundation of the layer of the pressure and reaction criteria. The status included two fundamental levels of the land's structure and function, and depicted the real condition of the land ecosystem under pressure [26].

Table 1. System of the LES evaluation index used for the BTH region.

Target Layer	Criterion Layer	Factor Layer	Index Layer	Direction *
Land ecological security	Pressure	Population	D1 Population density (person/km^2)	−
		Industry	D2 Proportion of secondary industries (%)	−
		Traffic	D3 Highway passenger traffic per unit of land area (10 thousand/km^2)	−
			D4 Road freight per unit of land area (10 thousand ton/km^2)	−
		Environment	D5 The usage of fertilizer per unit of cultivated area (ton/km^2)	−
			D6 Industrial dust emissions per unit of land area (ton/km^2)	−
			D7 Industrial wastewater discharge per unit of land area (10 thousand ton/km^2)	−
	State	Land structure	D8 Proportion of cultivated land (%)	+
			D9 Green coverage of urban built-up areas (%)	+
		Land function	D10 Food production per unit of land area (ton/km^2)	+
			D11 Economic density of the land (10 thousand CNY/km^2)	+
	Response	Population	D12 Population growth rate (%)	+
		Industry	D13 Per capita GDP (10 thousand CNY/person)	+
			D14 Proportion of tertiary industries (%)	+
		Traffic	D15 Transportation, warehousing, and postal investment per unit of land area (10 thousand CNY/km^2)	+
		Environment	D16 Comprehensive utilization rate of industrial solid waste (%)	+

* "+" and "−" represent positive and negative indicators, respectively.

This study established a system for an evaluation index of HED in the BTH region including five parts (Table 2), namely, innovative development, coordinated development, green development, open development, and shared development [30].

Table 2. System of the HED evaluation index used for the BTH region.

Primary Index	Secondary Index	Level III Index	Direction *
High-quality economics development	Innovative development	C1 Number of patents authorized per 10,000 persons	+
		C2 Intensity of investment into R & D (%)	+
	Coordinated development	C3 Demand structure (%)	+
		C4 Urban–rural structure (%)	−
		C5 Regional structure (%)	+
	Green development	C6 Energy consumption per unit of GDP (%)	−
		C7 Sewage treatment rate (%)	+
		C8 Rate of harmless treatment of domestic waste (%)	+
	Open development	C9 Proportion of foreign investment (%)	+
		C10 Degree of financial development (%)	+
	Shared development	C11 Proportion of workers' remuneration (%)	+
		C12 Elasticity of income growth (%)	+
		C13 Engel coefficient (%)	−

* "+" and "−" represent positive and negative indicators, respectively.

2.3.2. Entropy-Weighted TOPSIS Model

(1) Entropy-Weighted Method

The entropy-weighting method is an objective weighting method that determines the weight based on the high or low entropy of the indicator's information [26,30]. The data are first standardized using the range technique, and the weight is then determined using the entropy-weighting method. Equations (1)–(3) display the formulas. Matrix F_{ij} is the normalization matrix of the initial data, E_j is the information entropy, and W_j is the entropy weight.

$$F_{ij} = Y_{ij} / \sum_{i=1}^{m} Y_{ij} \tag{1}$$

$$E_j = -\ln(m)^{-1} \sum_{i=1}^{m} F_{ij} \ln\left(F_{ij}\right), 0 \le E_j \le 1 \tag{2}$$

$$W_j = \left(1 - E_j\right) / \sum_{j=1}^{n} \left(1 - E_j\right) \tag{3}$$

(2) TOPSIS

In this study, the LES and HED were evaluated using the TOPSIS approach. This is method is frequently chosen for multiobjective decision analyses of finite schemes in systems engineering that methodically examine the discrepancies between the ideal state and the actual level [26,30]. Equations (4)–(8) display the formulas. V_{ij} represents the weighted normalization matrix; V_j^+ represents the ideal positive solution; V_j^- represents the ideal negative solution; D_i^+ and D_i^-, respectively, represent the distance between the evaluated unit and the ideal positive and negative solutions; and U_i stands for the LES or HED of the research object.

$$V_{ij} = \left(Y_{ij} \times W_j\right)_{,m \times n} \tag{4}$$

$$V_j^+ = \{\max V_{ij}\}, j = 1, 2, \ldots, m \tag{5}$$

$$V_j^- = \{\min V_{ij}\}, j = 1, 2, \ldots, m \tag{6}$$

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j^+\right)^2};\ D_i^- = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j^-\right)^2} \tag{7}$$

$$U_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{8}$$

2.3.3. CCD Model

In this study, the coupling degree describes the degree of interaction in the LES–HED subsystems. The CCD is a quantitative indicator used to assess the condition or level of coordination of LES–HED subsystems. Equations (9) and (10) display the formulas [31]. C is the coupling degree, D is the CCD, U_L is the LES-, and U_H is the HED. The classification criteria of the stages of coupling are shown in Table 3. The classification criteria of the relationships of coupling coordination are shown in Table 4.

$$C = 2 \times \sqrt{(U_L \times U_H)/(U_L + U_H)^2} \tag{9}$$

$$D = \sqrt{C \times (0.5 \times U_L + 0.5 \times U_H)} \tag{10}$$

Table 3. The standards of the stages of coupling.

Degree of Coupling	Stages of Coupling
0–0.30	Low coupling
0.30–0.50	Antagonism
0.50–0.80	Running-in
0.80–1.00	High coupling

Table 4. The standards of the coupling coordination relationship.

Coupling Coordination Degree	Coupling Coordination Relationship
0.00–0.10	Extreme dissonance
0.10–0.20	Severe dissonance
0.20–0.30	Moderate dissonance
0.30–0.40	Mild dissonance
0.40–0.50	Near dissonance
0.50–0.60	Slight coordination
0.60–0.70	Primary coordination
0.70–0.80	Intermediate coordination
0.80–0.90	Good coordination
0.90–1.00	Quality coordination

2.3.4. PVAR Model

The PVAR model was applied to quantitatively analyze the interactive response mechanism between LES and HED in the BTH region. Equations (11) and (12) display the formulas. Y_{it} is the explanatory variable, LES and HED are explanatory variables, I is the region, t is time, n is the number of lags, α_{it} is the region's fixed effect, f_t is the time effect, $\prod_{nt} I$ is the coefficient matrix to be estimated, and μ_{it} is the error term with an independent and identical distribution.

$$Y_n = \alpha_{it} + f_t + \sum_{t-1}^{n} \prod_{nt} I_{i,t-n} + \mu_{it} \tag{11}$$

$$Y_{it} = \{LES, HED\} \tag{12}$$

2.3.5. Model of the Degree of Relative Development

The CCD model is unable to describe the status of the development of LES–HED subsystems accurately. This study used a model of the degree of relative development to examine the level of relative development [32]. Equation (13) displays the formula. E is the degree of relative development. The types of development are divided according to the degree of relative development, and the division criteria are shown in Table 5.

$$E = \begin{cases} U_H/U_L, U_L > U_H \\ U_L/U_H, U_L < U_H \\ 1, U_L = U_H \end{cases} \tag{13}$$

Table 5. Classification of the standards of the types of development.

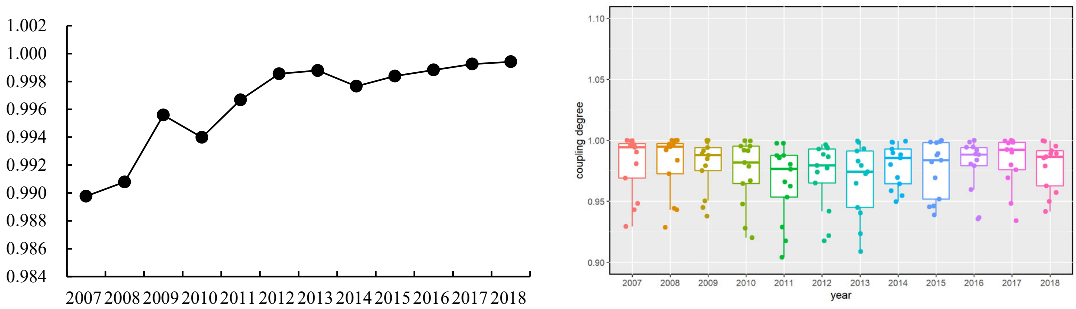
Contrasting Relationship	Degree of Relative Development	Type of Development
	$E > 0.6$	Slightly lagging HED
$U_L > U_H$	$0.4 < E \leq 0.6$	Significantly lagging HED
	$0 < E \leq 0.4$	Severely lagging HED
	$E > 0.6$	Slightly lagging LES
$U_L < U_H$	$0.4 < E \leq 0.6$	Significantly lagging LES
	$0 < E \leq 0.4$	Severely lagging LES
$U_L = U_H$	$E = 1$	Synchronous development

3. Results

3.1. Characteristics of Coupling Coordination

3.1.1. Degree of Coupling

We determined the strength of the coupling in the LES–HED subsystems in the BTH region between 2007 and 2018 using the CCD model. Over the previous 12 years, the degree of coupling has progressively trended upward (from 0.9898 to 0.9994), and the BTH area is at a stage of high coupling (Figure 3). The cities of the BTH have a degree of coupling between 0.92 and 1.00, which indicates that they are at the stage of high coupling (Figure 3). According to the findings, there was a high correlation between LES and HED in the BTH region, and it was gradually improving.

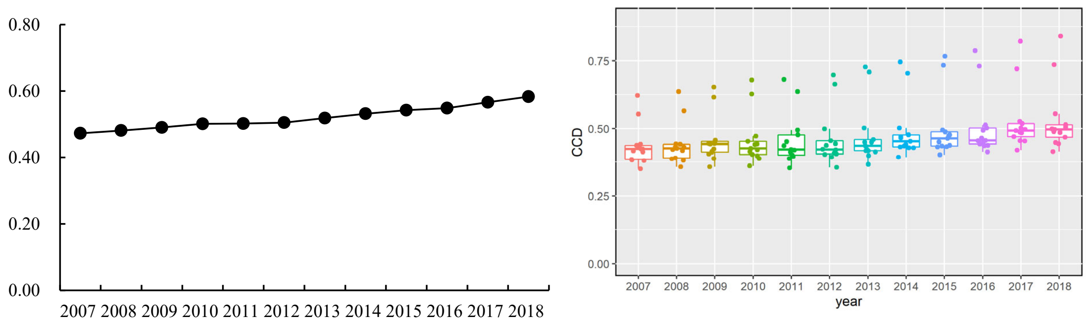


(**a**) (**b**)

Figure 3. The degree of coupling of the LES–HED subsystems: (**a**) degree of coupling in the BTH region; (**b**) degree of coupling in the cities of the BTH.

3.1.2. Coupling Coordination Degree

We estimated the CCD of LES–HED subsystems in the BTH area between 2007 and 2018 using the CCD model (Figure 4). Over the previous 12 years, the CCD has progressively risen (from 0.47 to 0.58), changing the relationship of coordination from virtual dissonance to slight coordination. In particular, the CCD grew from 0.47 to 0.50 in 2010, and the coupling coordination was on the verge of dissonance, showing that the impact of the LES–HED subsystems was not clear, and the relationship of coordination was weak. The CCD grew from 0.50 in 2010 to 0.58 in 2018, indicating that there was some mutual effect but no improvement in the coupling coordination, which was barely correlated.



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

Figure 4. The CCD of the LES–HED subsystems: (**a**) CCD in the BTH region; (**b**) CCD in the cities of the BTH.

Within the research area's cities, the CCD of the LES–HED subsystems showed a general upward trend and included good coordination, moderate coordination, strong coordination, and barely detectable dissonance. The CCD increased over time, rising from 0.3499–0.4422 in 2007 to 0.4141–0.8402 in 2018, and changed from mild dissonance to strong coordination (Figure 4). The spatiotemporal pattern is shown in Figure 5, which clearly reflects the CCD of each city in 2007, 2010, 2015, and 2018. The general spatial pattern throughout the research period was "center > periphery". There is no doubt that the CCD in Beijing and Tianjin was superior to that in other areas. The year 2018 saw Beijing and Tianjin establish a strong level of coordination. Shijiazhuang, Langfang, and Qinhuangdao were all quite weak and slight coordinated. The other nine cities (Chengde, Zhangjiakou, Tangshan, Baoding, Cangzhou, Hengshui, Xingtai, and Handan) were near dissonance. The evolution of the curve of the relationship of coupling coordination showed a clear wave shape (Figure 6), where the coupling coordination degree steadily improved and the curve's peak advanced continuously, showing that the LES and HED system were developing sustainably and in an orderly fashion. The proportion of cities with mild dissonance gradually decreased (30.77%→23.08%→0→0), the proportion of cities with near dissonance increased and then decreased (53.85%→61.54%→84.62%→61.54%), the proportion of cities with slight coordination decreased and then increased (7.69%→0→0→23.08%), the proportion of cities with primary coordination first increased and then decreased (7.69%→15.38%→0→0), the proportion of cities with intermediate coordination increased (0→0→15.38%→7.69%), and the proportion of cities with good coordination increased (0→0→0→7.69%).

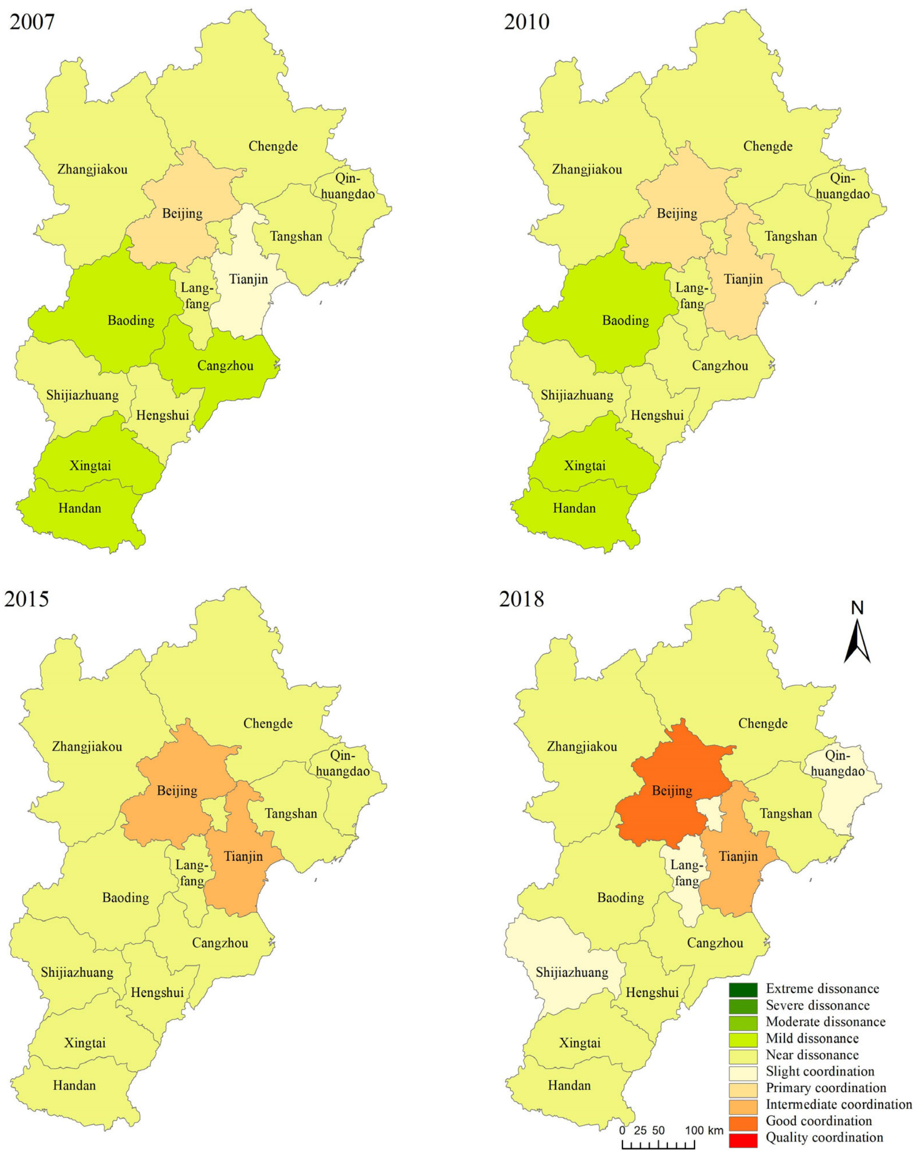


Figure 5. The relationships of coupling coordination in the cities of the BTH.

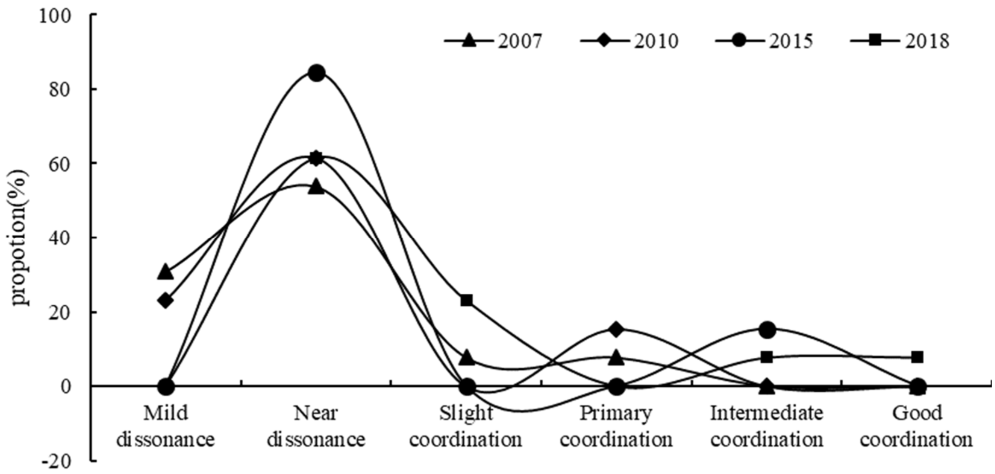


Figure 6. Evolution of the curve of the relationship of coupling coordination.

3.2. Results of the PVAR Model

3.2.1. Unit Root Test

Before performing a dynamic analysis, a unit root test was required (Table 6). A single test method is easily prone to error. This study used the HT and IPS tests because the original sample included short-run panel data. It turned out that the initial data did not pass the stationarity test and that the data were unstable. However, the first-order difference value of the original data passed the 1% significance level, meeting the same-order single integer condition. It can be seen that LES and HED are first-order single integer data.

Table 6. Unit root tests.

Variable	Results	IPS	HT	Conclusion
ln LES	Statistic measurement *p*-value	0.4596 0.6771	0.3335 0.0596	Unstable data
ln HED	Statistic measurement *p*-value	0.3526 0.6378	0.4320 0.3502	Unstable data
DlnLES	Statistic measurement *p*-value	−7.0049 0.0000	−0.1701 0.0000	Stable data
DlnHED	Statistic measurement *p*-value	−5.0849 0.0000	−0.2352 0.0000	Stable data

3.2.2. Selection of the Optimal Lag Order

The optimal lag order was determined first, followed by estimation of the model. In this study, the test was performed using the information criterion, and the lag orders were set to 1, 2, 3, 4, and 5. The values of the information criterion were calculated for AIC, BIC, and HQIC. The test results indicated that the best lag order was 1 (Table 7).

Table 7. Selection of the optimal lag order.

Lag Period	AIC	BIC	HQIC
1	−3.96962	−3.24929	−3.67697
2	−3.94210	−3.06829	−3.58757
3	−3.69766	−2.64257	−3.27090
4	−3.56758	−2.2943	−3.05573
5	−2.54992	−1.00809	−1.93748

3.2.3. Cointegration Tests

LES and HED had the same order of single integration, which met the basic conditions of the test of the cointegration relationship. This study tested the possible cointegration relationship of LES–HED subsystems and examined whether there was a long-term and stable equilibrium in the relationship of LES–HED subsystems and whether they could develop dynamically. A single test method made it easy to introduce errors. This study selected two methods for the cointegration tests, including the Kao test and the Pedroni test. The results showed that the statistical results of the ADF (augmented Dickey–Fuller) test obtained by the Kao test passed the significance level of 10% and that the statistical results of the modified PP (Phillips–Perron) and ADF tests obtained by the Pedroni test passed the significance level of 1% (Table 8). Therefore, there was a long-term and stable equilibrium in the relationship between LES and HED, and the two could develop dynamically.

Table 8. Cointegration tests.

Test	Presupposition	Statistical Results	Statistical Measurement	*p*-Value
Kao test	No cointegration relationship	Modified Dickey–Fuller	0.0550	0.4781
		Dickey–Fuller	−2.3908	0.0084
		Augmented Dickey-Fuller	1.2966	0.0974
		Unadjusted modified Dickey–Fuller	−1.4904	0.0681
		Unadjusted Dickey–Fuller	−3.3951	0.0003
Pedroni test		Modified Phillips–Perron	0.9357	0.1747
		Phillips–Perron	−4.0997	0.0000
		Augmented Dickey–Fuller	−5.5907	0.0000

3.2.4. Granger Causality Tests

Granger causality tests were used to verify the statistical causation of the variables. HED is not the Granger reason for LES, and LES is the Granger reason for HED (Table 9). Therefore, an improvement in LES promoted HED, but the impact of HED on LES was limited in the BTH region.

Table 9. Granger causality tests.

Presupposition	F-Statistic	*p*-Value	Yes or No
HED is not the Granger reason for LES	−0.8153	0.4149	Yes
LES is not the Granger reason for HED	2.4768	0.0133	No

3.2.5. Analysis of the Interaction Mechanism

The impulse response function can visualize the dynamic interactive effects between different variables. Impulse response analysis was conducted for LES–HED subsystems, and Monte Carlo simulation was conducted to explore the dynamic trends of the interactions of LES–HED subsystems over the following 6 years (Figure 7). The LES–HED subsystems showed characteristics of self-improvement, and their impact gradually decreased with the passage of time. The effect of LES on itself showed a tendency to rise and then fall, with the maximum value appearing in the first stage and stabilizing after about two stages. The impact of HED on itself rose at first and then fell. The maximum value of the impact also appeared in the first phase, and the impact was stable after about three phases. The impact of LES on HED showed a positive fluctuation, but the amplitude of the change was relatively small. The maximum value of the impact appeared in the first phase, and the impact was stable after about two phases. The result showed that although HED had a driving effect on LES, the effect was not significant. The effect of HED on LES showed a tendency to rise and then fall, with the maximum value appearing in the first phase and becoming stable after about three phases. The results showed that LES had an obvious supporting effect on HED, but the effect gradually decreased over time.

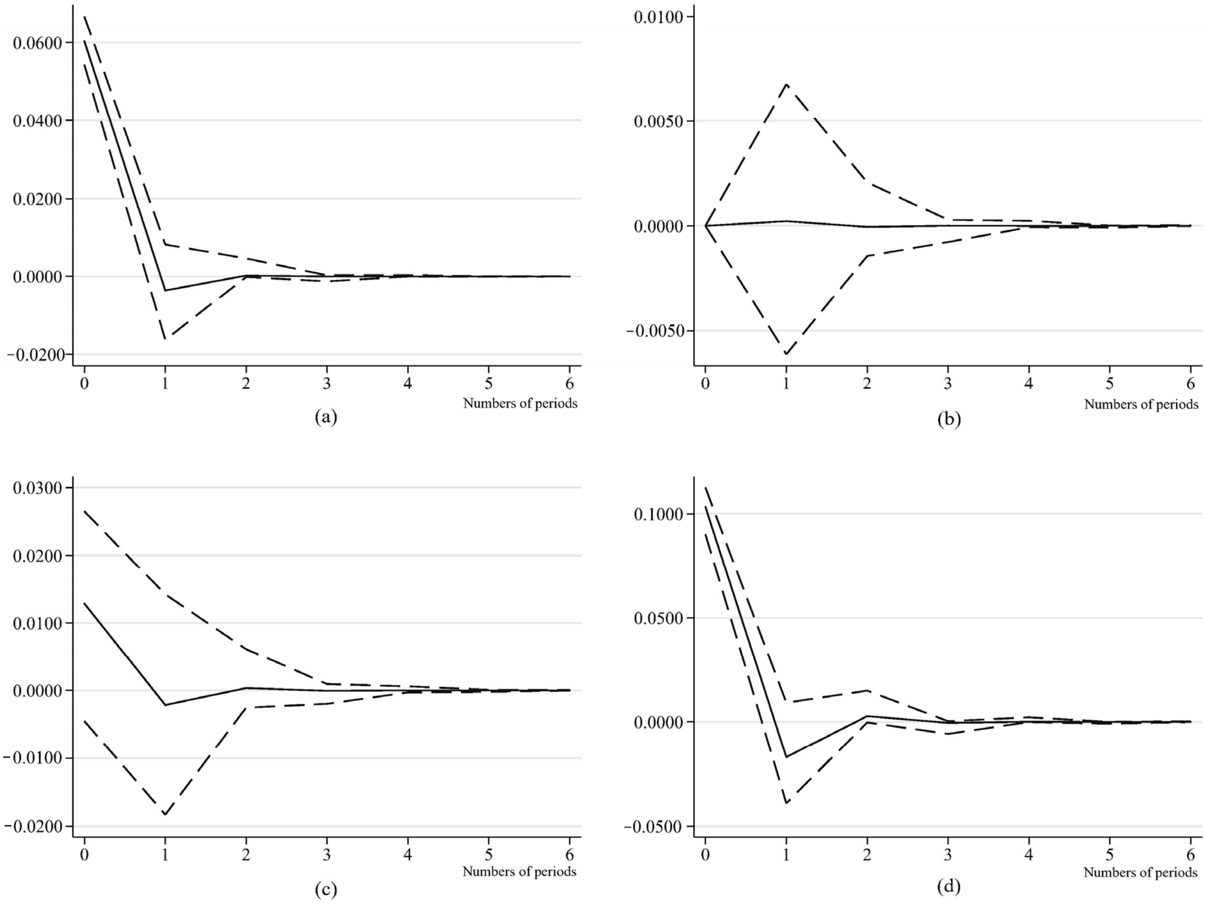


Figure 7. Analysis of the impulse response: (**a**) the response of LES to its own impact; (**b**) the response of LES to the impact of HED; (**c**) the response of HED to the impact of LES; (**d**) the response of HED to its own impact.

3.3. Types of Development

On the basis of the model of relative development and the classification standards of the types of development, we divided the development patterns of the cities in 2007, 2010, 2015, and 2018 (Figure 8). The development patterns within the cities of the study area included slightly lagging LES, slightly lagging HED, and significantly lagging HED. The proportion of cities with slightly lagging HED first rose and then descended (46.15%→53.85%→61.54%→38.46%). The proportion of cities with slightly lagging LES first decreased and then increased (30.77%→7.69%→7.69%→30.77%). The proportion of cities with significantly lagging HED first increased and then decreased (23.08%→38.46%→30.77%→30.77%). From the perspective of spatial patterns, the cities with slightly lagging LES were mainly distributed in the northern part of the research area, such as Chengde, Zhangjiakou, Qinhuangdao, and Hengshui. The cities with slightly lagging HED were mainly distributed in the central part of the research area, such as Beijing, Tianjin, Langfang, Baoding, and Xingtai. The cities with significantly lagging HED were mainly distributed in the southern part of the research area, such as Tangshan, Cangzhou, Shijiazhuang, and Handan.

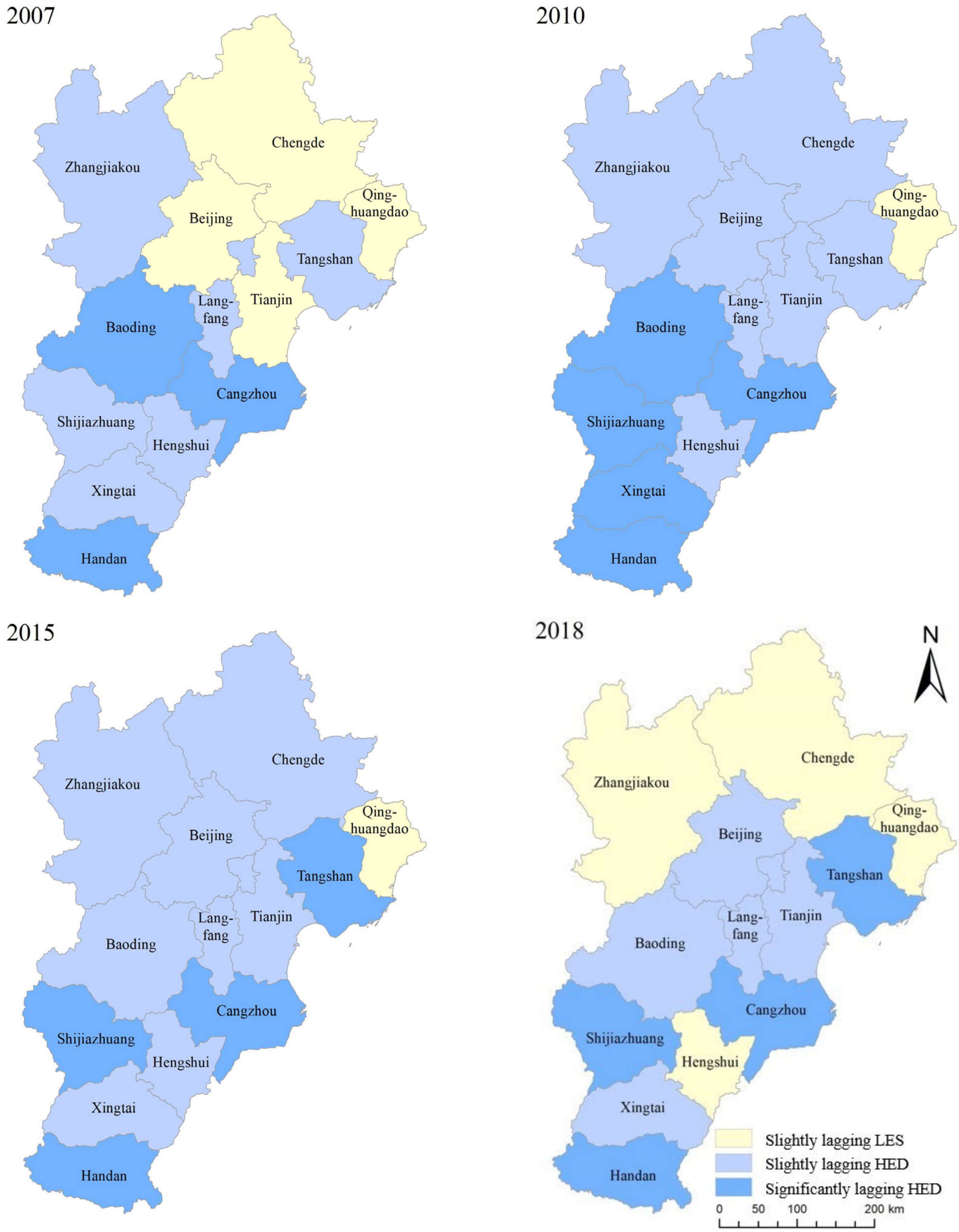


Figure 8. The types of development in the cities of the BTH.

4. Discussion

The CCD model based on coupling theory can help monitor the dynamics, depict the evolutionary processes, and identify whether the coupling system has a coordinated development pattern, which is essential for making decisions to achieve coordinated regional development [33]. This research showed that the area is in a stage of high coupling stage, the CCD has generally been at a low level but continues to improve, and the interaction between the two systems has gradually strengthened and developed in an orderly direction according to the CCD model. In line with this, this study also explored the interactive mechanism of the two systems with the PVAR model. The research showed that a long-term and stable equilibrium existed in the LES–HED subsystems. An increase in LES can promote HED, but an increase in HED has less effect on LES. Due to the complex and systematic coupling between LES and HED, this study demonstrated that the CCD model and PVAR model were efficient tools for studying the coupling coordination and mechanism of the interactions of LES–HED subsystems in sustainable regional development, as well as for understanding the effects of synergistic interactions.

The key to realizing the development of coupling coordination in LES–HED subsystems is to promote a positive relationship between the two subsystems. The CCD and PVAR models could reflect the strength of the correlation of LES–HED subsystems well but could not represent the level of relative development of the two systems. Therefore, this study used the model of relative development to analyze the status of development in the LES–HED subsystems. The research showed that the cities with slightly lagging LES were mainly distributed in the northern part of the research region, the cities with slightly lagging HED were mainly distributed in the middle part of the research region, and the cities with significantly lagging HED were mainly distributed in the southern part of the research region. HED should be promoted in five aspects in areas where it lags behind: comprehensively improving innovative capacity, promoting coordinated regional development, forming a new pattern of opening up, accelerating green and shared development, and implementing differentiated development programs. Specific policy recommendations touching on six aspects should be proposed in areas where LES is lagging behind: establishing a mechanism of coordinated development, optimizing the spatial distribution of the population, promoting integrated industrial development, optimizing a comprehensive transportation network, strengthening ecological protection of the land, and improving the level of LES appropriately.

Considering the coupling stage, coordination relationships, and types of development, the study clarified the functional division of coordinated development. In 2018, the research area was in the high coupling stage. According to the coordination relationship and type of development, the study area was divided into six functional zones. The leading development zone of HED mainly included Tangshan, Cangzhou, and Handan; these areas were nearly dissonant, and the HED was significantly lagging. The key economic development zone of HED mainly included Baoding and Xingtai; these areas were nearly dissonant, and the HED was slightly lagging. The key development zone of LES mainly included Chengde, Zhangjiakou, and Hengshui; these areas were nearly dissonant, and the LES was slightly lagging. The zone of steady development of LES mainly included Qinghuangdao; the area was barely coordinated, and the LES was slightly lagging. The zone of steady development of HED mainly included Langfang and Shijiazhuang; these areas were barely coordinated, and the HED was slightly or significantly lagging. The zone of sustainable development of HED mainly included Beijing and Tianjin; these areas had good coordination or intermediate coordination, and the HED was slightly lagging.

This study theoretically analyzed the close relationship between the LES–HED subsystems, explored the coupling coordination and mechanism of the interactions of the subsystems using the CCD model and PVAR model, and used the model of relative development to classify the types of regional development, which could provide a basis for selecting paths of sustainable development. However, due to data limitations and imperfect knowledge, this study still has room for further improvement in the modeling process. First, selecting evaluation metrics based on theoretical analysis will lead to more reliable results. For example, an analysis of the driving force was used to determine the key factors affecting LES or HED. Second, the coefficients of contribution in the CCD model's equations are usually defined on the basis of previous knowledge, which may lead to distorted results in the evaluation because of subjectivity. Therefore, we could consider defining coefficients of contribution based on synergy theory in future studies [34].

5. Conclusions

Using the BTH region as the research region, this research quantitatively measured the state of coupling coordination of the LES–HED subsystems and analyzed the spatial and temporal properties of their coordination relationships based on data obtained from 2007 to 2018. The PVAR model was then used to analyze the interaction–response mechanism of the LES–HED subsystems, and a model of the degree of relative development was used to classify the types of the regional development. The following are the main conclusions reached and drawn in this study.

(1) The BTH region is in a stage of high coupling, and the degree of coupling showed a trend of gradual enhancement.
(2) During the study period, with a slow increase in CCD (from 0.47 to 0.58), the coordination relationship changed from near dissonance to slight coordination in the BTH region. The CCD rose from 0.3499–0.4422 (2007) to 0.4141–0.8402 (2018) and evolved from mild dissonance to good coordination over time within the research area's cities. The spatial distribution was characterized as being low in the central area and high in the peripheral area. The CCD showed a clear wave-like curve of evolution over time.
(3) A long-term and stable equilibrium relationship existed in the LES–HED subsystems. The two systems of LES and HED showed characteristics of self-improvement. HED had a positive driving effect on LES, but the effect was not obvious. LES had an obvious supporting effect on HED, but the effect gradually decreased over time.
(4) The patterns of development within the cities of the study area included three types of development. The cities with slightly lagging HED were scattered in the middle of the region; the proportion of these cities was the highest. Cities with slightly lagging LES were scattered throughout the north of the region. Cities with significantly lagging HED were mostly concentrated in the south. According to the coordination relationship and type of development, the research was divided into six functional zones, namely, the leading development zones of HED, the key development zones of HED, the key development zone of LES, the steady development zones of LES, the steady development zones of HED, and the sustainable development zones of HED.

Given the spatial variability in the coupled and coordinated development of LES–HED subsystems, it is necessary to implement different strategies of development. This study can inform decisions to promote the coordinated development of LES–HED subsystems for sustainable regional development.

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