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Research Article

Measuring and Fitting the Relationship between Socioeconomic Development and Environmental Pollution: A Case of Beijing–Tianjin–Hebei Region, China

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The Beijing–Tianjin–Hebei (BTH) region is a top urban agglomeration of China but has the problem of severe environmental pollution. Most of the current researches on the sustainable development of this region only concentrate on the environmental pollution itself and ignore its relationship to the socioeconomic development. In this research, an entropy-based coupling model, a polynomial equation with partial least squares algorithm, and socioeconomic and environmental data in 2006–2015 were used to measure and fit the above relationship. Empirical analysis led to the following conclusions. (1) Beijing, Tianjin, and Hebei presented similar socioeconomic development modes but different environmental pollution modes. (2) The social economy of the BTH region has been developing at the expense of environmental pollution, but the environmental cost has been decreasing year by year. (3) At present, the BTH region has huge potential to improve its environment. (4) Increasing the investment in the treatment of industrial pollution in Tianjin and mitigating the soot (dust) emissions in Tianjin and Hebei are the major environmental policy directions. (5) Controlling the development of smelting and pressing of ferrous metals and other building material sectors in Hebei is the major economic policy direction.

1. Introduction

The Beijing–Tianjin–Hebei (BTH) region is one of the most dynamic but seriously polluted urban agglomerations in China [1, 2]. The aim of this research is to measure the coupling relationship between socioeconomic development and environmental pollution in the BTH region, fit the changing trend of this relationship, and offer policy implications to guide the sustainable development of this region.

The BTH region is located in the heart of China's Bohai Rim. It covers about 2.26% of China's territory (217.16 thousand km^2) and is inhabited by almost 8.09% of the population of China (112.47 million people) [3–5]. At present, the BTH, Pearl River Delta, and Yangze River Delta are China's top three urban agglomerations. The three regions produce approximately 10.20%, 10.91%, and 20.62% of China's GDP and contributed 11.26%, 14.45%, and 26.41% to GDP growth, respectively [1]. However, unlike the latter two regions, the BTH region faces serious environmental pollution. On 22 July 2018, a report released by China's Ministry of Ecology and Environment shows that one-fourth of the most polluted cities in China are located in the BTH region and nearly all cities in this region do not meet the air quality standards recommended by the World Health Organization [2, 6]. Environmental pollution not only has led to the deterioration of living conditions in the BTH region but also threatens the economic development [7]. China will face the risk of losing this important economic growth engine if the effects of environmental pollution are not mitigated.

Although the environmental and economic issues of the BTH region have gained the attention of researchers, most studies focus on three areas as follows. (1) Impacts of environment pollution: Zhang et al. [8] used city-level panel data to explore the influence of urban pollution on labor supply. Their research results indicated that the above impact is nonlinear, and the extent of impact is affected by income level. Zhu et al. [9] adopted Lagrange Multiplier test and Spatial Durbin Model to investigate the relationship between foreign direct investment and sulfur dioxide (SO_2) emissions in the BTH region. They confirmed the existence of the causality of the above two variables. (2) Cause and countermeasure of environment pollution: A positive Matrix Factorization research conducted by Gao et al. found that PM2.5 pollution in the BTH region was dominated by vehicle and combustion emissions, including coal burning and biomass combustion, and soil and construction dust emissions [10]. Wang et al. [11] evaluated the impacts of thermal power plants on air quality in the BTH region. These emissions contributed 38%, 23%, 23%, 24%, and 24% of CO_2, SO_2, NO_2, PM2.5, and PM10, respectively. Based on studies on pollution sources, Wang and Zhao [12] proposed a Joint Prevention and Control of Atmospheric Pollution program to control PM2.5 and PM10 in the BTH region. (3) Adjustment directions for development policies to mitigate environment pollution: Zhang et al. [13] proposed a vulnerability assessment method of atmospheric environment associated with human impact to identify and prioritize the undesirable environmental changes. Decision makers can make appropriate development policies based on the vulnerable results. Fang et al. [14] applied Gini coefficient and Technique for Order Preference by Similarity to an Ideal Solution to measure the performance of collaborative development in the BTH region. They proposed that optimizing investment structures and establishing an ecological compensation mechanism contribute to smooth collaborative development. These studies offer useful suggestions to guide economic development and/or pollution mitigation, but fail to draw policy implications based on descriptions of the general relationship between economy and environment in terms of coupling degree and driving factor. The goals of this research are measuring and fitting the coupling relationship between socioeconomy and environment in the BTH region. Based on the empirical results, some policy implications are offered to prompt the sustainable development.

In 1955, Kuznets [15] proposed a hypothesis that the relationship between various indicators of income inequality and economic development presents an inverted U-shaped curve. In the early 1990s, this inverted U-shaped curve was used by Grossman and Krueger [16, 17] to fit the relationship between economic growth and environmental pollution. It was later named Environmental Kuznets Curve (EKC) by Panayotou [18]. In the next two decades, the EKC analysis was widely used in many countries and regions [19, 20]. However, when used in these studies, the EKC has two limitations. For one thing, the EKC needs only one indicator to reflect economic growth and one indicator to measure environmental pollution. However, both economic growth and environmental pollution are very complex, and it is difficult to select one indicator to represent each of them. For example, the economic development of China manifests not only as scale expansion but also as structure upgrade. Obviously, both aspects have impacts on environmental pollution, and using one indicator (e.g., GDP output) in EKC analysis is hence improper. For another, as a developing country, China also has unstable economic and environmental policies. Thus, EKC presents different shapes in China for different indicators and time spans. Some studies supported the inverted U shape [21–23], but others recommended different figures [24, 25]. The best fitting equation for the EKC in China is difficult to ascertain, especially in the short term.

In this research, a multi-indicator system and an entropy weight evaluation method were used to evaluate the socioeconomic development and environmental pollution levels. Derived from the entropy information theory, this method ascertains the weight of an indicator is based on its information scale. This idea can ensure that the obtained weights have the maximum differentiation ability to the evaluation objects [26]. It is especially suitable for the situations that the importance of the evaluation indicator is close, just as the evaluation issue of this research. To precisely fit the relationship between the above two levels, a coupling coordination degree model and a polynomial equation that has the ability to fit a variety of trends were used. Furthermore, the partial least squares (PLS) algorithm was used to estimate the parameters of the multivariate equation. Compared with the traditional ordinary least squares (OLS) algorithm, the PLS can obtain more stable parameters using small samples.

The remainder of this paper is organized as follows. Section 2 illustrates the methodology and data used in this research. Section 3 lists the modelling results, and Section 4 discusses them. Section 5 concludes the research and offers policy implications.

2. Methods and Data

2.1. Coupling Coordination Degree Model. To measure the coupling coordination degree of the socioeconomic development and environmental pollution, the scores of the above two indicators should be calculated first by the entropy weight evaluation method. The modelling process of the entropy weight evaluation method is introduced as follows.

Supposing m indicators are used to evaluate n objects, and x_{ij} is the static of the jth indicator in the ith object, the preprocessing step to the indicator statistics is

$$y_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}. \quad (1)$$

The algorithm of (1) can eliminate the impacts of the static units to the evaluation results. Based on the pre-processing results, the information entropy of the jth indicator is a measure of its chaos situation, calculated by

$$e_j = -\frac{\sum_{i=1}^{n} y_{ij} \ln y_{ij}}{\ln n}. \quad (2)$$

Obviously, $e_j \in (0, 1]$. The more information jth indicator has, the larger e_j is. Based on the information entropy, the evaluation weight of the jth indicator is obtained by

$$w_j = \frac{\left(1 - e_j\right)}{\sum_{j=1}^{m} \left(1 - e_j\right)}. \quad (3)$$

Then, the evaluation result (score) of the ith object is

$$R_i = \sum_{j=1}^{m} y_{ij} w_j \quad (4)$$

Supposing R_S and R_E are evaluation scores of socioeconomic development and environmental pollution, respectively, the coupling coordination degree is as follows [27]:

$$D = \sqrt{CT}, \tag{5}$$

where $C = \sqrt{R_S R_E/[(R_S + R_E)/2]^2}$ and $T = \alpha R_S + \beta R_E$; α and β denote the contributions of socio-economic development and environmental pollution to the comprehensive system, respectively.

The difference of R_S and R_E identifies the lagging factor. For example, $R_S > R_E$ implies that socioeconomic development is ahead of environment pollution.

2.2. Polynomial Fitting Equation. The polynomial equation is written as follows:

$$y = b_0 + b_1 t + b_2 t^2 + \cdots b_p t^p, \tag{6}$$

where t refers to time; y is explained variable; and b_0–b_p are regression parameters.

The Weierstrass approximation theorem has proven that any continuous function can be uniformly approximated by (6) [28].

The specific form (number of independent variables) of (6) is determined by the following akaike information criterion (AIC) and schwarz criterion (SC).

$$AIC = e^{2p/n} \frac{RSS}{n}, \tag{7}$$

$$SC = n^{p/n} \frac{RSS}{n}, \tag{8}$$

where n is the sample number used for parameter estimation; RSS is the residual sum of squares.

The above two criteria have similar function. The lower their values are, the better the equation is.

Considering the equation structure of (6), the multicollinearity phenomenon may well exist between the explanatory items. Moreover, the smaller sample size can increase the multicollinearity extent [29]. If the traditional OLS algorithm is used to estimate the parameters of (6), unstable estimations are obtained. The following PLS algorithm can obtain stable regression parameters in the abovementioned environment [30].

Let

$$X = \left[x_{ij}\right] = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 2 & 2^2 & \cdots & 2^p \\ \cdots & \cdots & \cdots & \cdots \\ n & n^2 & \cdots & n^p \end{bmatrix}, \tag{9}$$

and the following preprocessing process is essential:

$$E_0 = \left[x_{ij}^*\right] = \left[\frac{x_{ij} - mean\left(x_j\right)}{std\left(x_j\right)}\right], \tag{10}$$

$$F_0 = \left[y_i^*\right] = \left[\frac{y_i - mean\left(y\right)}{std\left(y\right)}\right]. \tag{11}$$

The first component can be extracted by the following:

$$c_1 = E_0 w_1. \tag{12}$$

where $w_1 = (E_0^T * F_0)/\|E_0^T * F_0\|$ and $\|w_1\| = 1$.

Let F_1 and E_1 be the residual vector (matrix) of F_0 and E_0 explained by c_1, respectively, and replace E_0 and F_0 with F_1 and E_1 in (12); the second component (c_2) is then extracted. Using a similar algorithm, more components can also be obtained.

The number of extracted components must be proper because too many components will introduce stochastic information into the final equation. In general, as the first component (c_1) represents the most important quantity relationship between the explained and the explanatory variables, it should be directly introduced into the final equation. Beginning with the second component (c_2), the importance of extracted components should be tested one by one. Reserving or abandoning a component is decided by the following cross efficiency indicator [31].

When testing the importance of the h_{th} component, a fitting equation using the first h components and n-1 samples (the i_{th} sample is excluded) is estimated, and the fitting result of this equation to the i_{th} sample is written as $\hat{y}_{h(-i)}$. Moreover, a fitting equation using the first h-1 components and all samples is also estimated, and the fitting result of this equation to the i_{th} sample is written as $\hat{y}_{(h-1)i}$. Using the two abovementioned fitting results, the cross efficiency of the h_{th} exponent is measured by

$$Q_h^2 = 1 - \frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_{h(-i)}\right)^2}{\sum_{i=1}^{n}\left(y_i - \hat{y}_{(h-1)i}\right)^2}. \tag{13}$$

In (13), a small $\sum_{i=1}^{n}(y_i - \hat{y}_{h(-i)})^2$ implies that the first h components have contained the useful information and a large $\sum_{i=1}^{n}(y_i - \hat{y}_{(h-1)i})^2$ means the first h-1 components are not sufficient. According to the statistic experience, for the h_{th} exponent, $Q_h^2 \geq 0.0975$ implies that the importance of this component is notable and it should be reserved. Otherwise, it should be abandoned. As the importance of variables decreases one by one and if the h_{th} component is abandoned, there is no need to test the importance of the next component (abandoned directly). However, if the h_{th} component is reserved, the importance of the next component should be tested until the first abandoned component appears. As the process of component extraction is efficient in gathering useful information, the number of reserved components usually does not exceed three.

Supposing m components are reserved, an equation between F_0 and the components can be obtained by the OLS algorithm, as follows:

$$F_0 = r_1 c_1 + r_2 c_2 + \cdots r_m c_m \tag{14}$$

Using the inverse calculation of the preprocessing and component extracting processes, the linear regression equation of y to t can be obtained from (14).

Table 1: Selected indicators and their corresponding codes.

Socio-economic development		Environmental pollution	
Code	Indicator	Code	Indicator
S_1	Resident population	E_1	Investment completed in the treatment of industrial pollution
S_2	Annual disposable income per capita	E_2	Total energy consumption
S_3	Gross product of primary industry	E_3	Total volume of industrial waste gas emission
S_4	Gross product of the secondary industry	E_4	Total volume of sulfur dioxide emission
S_5	Gross product of the tertiary industry	E_5	Total volume of soot (dust) emission

2.3. Data Selection. In this research, we selected five indicators to evaluate the socioeconomic development and environmental pollution levels, respectively, as shown in Table 1. These indicators cover most aspects of socioeconomic development and environmental pollution. To facilitate the follow-up analysis, a code was assigned to each indicator.

Statistics of S_1 and E_1 were selected from the China Statistic Yearbook (2007-2016) [1]; S_2–S_5 and E_2 were obtained from the Beijing Statistical Yearbook (2015-2016), Tianjin Statistical Yearbook (2009-2016), and Hebei Economic Yearbook (2016) [3–5]; E_3–E_5 were obtained from the China Statistical Yearbook on Environment (2007-2016) [32]. China is presently adopting the "Five-year Plan" management mode [33]. Development policies are adjusted every five years. The year 2006 is the first year of China's 11th five-year plan, and during which period, the environmental problems in the BTH region were taken seriously for the first time. Considering that the latest available data are from 2015, the timespan of sample collection covered 2006–2015. Table 2 shows the above selected data.

3. Results

3.1. Coupling Coordination Degree. Using the entropy weight evaluation method and data in Table 2, the evaluation weight vectors for socio-economic development and environmental pollution in each province were calculated. It is important to note that E_1 (investment completed in the treatment of industrial pollution) is an inverse indicator for environmental pollution level. Thus, values of this indicator introduced into the entropy weight evaluation method are reciprocals. Moreover, besides Beijing, Tianjin, and Hebei, the indicator statics for the whole BTH region were obtained using data in Table 2, and the evaluation weight vector was also calculated. These weight results are shown in Table 3.

The evaluation scores of socioeconomic development and environmental pollution were obtained using data in Tables 2 and 3 and entropy weight evaluation method. Considering that socio-economic development and environmental pollution are equally important, α and β are equal to 0.5 when calculating the coupling coordination degree. Inputting the obtained evaluation scores into (5), the coupling coordination degrees were calculated. Table 4 lists the above results.

3.2. Trend Fitting. Trends of socioeconomic development and environmental pollution scores and coupling coordination degree of the BTH region were fitted using (6). Considering that the linear trend is too simple, and the trend of high-order items is very sheer, this research considered the forms of $p = 2$ and $p = 3$. The equation parameters were estimated by the abovementioned PLS algorithm. After parameter estimation, the AIC and SC indicators of each equation were calculated. All related results are shown in Table 5.

In Table 5, the AIC and SC results of $p = 2$ are both larger than those of $p = 3$ for each explained variable. That is, $p = 2$ in (6) is the best selection to fit the trends of socioeconomic development score (R_S), environmental pollution score (R_E), and coupling coordination degree (D) of the BTH region.

4. Discussion

4.1. Indicator Contribution Analysis. Indicator weights in Table 3 imply the relative importance of indicators for socioeconomic development and environmental pollution changes. Pie charts for these weights can reveal interesting information, as shown in Figure 1.

As shown in Figure 1, compared with environmental pollution, weights of indicators for socioeconomic development (S_1–S_5) are similar among different regions. This means that Beijing, Tianjin, and Hebei have similar socioeconomic development modes during 2006–2015. In general, gross product of the tertiary industry (S_5) plays the key role in the improvement of the socioeconomic level. The importance of gross product of secondary industry (S_4) and annual disposable income per capita of urban households (S_2) is roughly equal. During the improvement process of socioeconomic level, the contribution of gross product of primary industry (S_3) is a little less than the above two indicators and that of population (S_1) is negligible.

The above results indicate that this region has been developing to the stage of post-industrialization [34]. Compared with the primary and secondary industries, the tertiary industry is more important in prompting the economic development in this region. In fact, the value added share of the tertiary industry in GDP has increased from 48.45% to 56.14% during 2006–2015. The major risk of socioeconomic development in this region comes from the relatively low growth rate of population. From 2006 to 2010, the average annual growth rate of population is only 1.7%. This may cause workforce shortages, aging, and many other problems.

Figure 1 also shows that the three regions present different environmental pollution modes. In Beijing, investment

Table 2: Selected data of the three regions for each indicator during 2006–2015.

Region	Year	S_1	S_2	S_3	S_4	S_5	E_1	E_2	E_3	E_4	E_5
Beijing	2006	16.01	19.98	8.54	217.79	585.45	1.01	53.99	464.10	0.176	0.050
	2007	16.76	21.99	9.94	249.39	725.35	0.81	57.48	514.60	0.152	0.048
	2008	17.71	24.73	11.14	259.29	841.07	0.78	57.86	431.60	0.123	0.048
	2009	18.60	26.74	11.68	280.42	923.20	0.34	60.09	440.80	0.119	0.044
	2010	19.62	29.07	12.27	332.57	1066.52	0.19	63.60	475.00	0.115	0.049
	2011	20.19	32.90	13.44	367.80	1243.95	0.11	63.97	489.65	0.098	0.066
	2012	20.69	36.47	14.81	396.26	1376.87	0.33	65.64	326.37	0.094	0.067
	2013	21.15	40.32	15.96	429.26	1534.86	0.43	67.24	369.22	0.087	0.059
	2014	21.52	43.91	15.90	454.48	1662.70	0.76	68.31	356.92	0.079	0.057
	2015	21.71	52.86	14.02	454.26	1833.17	1.00	68.53	367.60	0.071	0.049
Tianjin	2006	10.75	14.28	10.34	245.71	190.23	1.50	45.00	651.20	0.255	0.080
	2007	11.15	16.36	11.02	289.25	225.00	1.51	49.43	550.60	0.245	0.074
	2008	11.76	19.42	12.26	370.98	288.67	1.68	53.64	600.50	0.240	0.070
	2009	12.28	21.40	12.89	398.78	340.52	1.80	58.74	598.30	0.237	0.071
	2010	12.99	24.29	14.56	484.02	423.86	1.65	60.85	768.60	0.235	0.065
	2011	13.55	26.92	15.97	592.83	521.92	1.53	67.81	891.93	0.231	0.076
	2012	14.13	29.63	17.16	666.38	605.85	1.26	73.26	903.22	0.225	0.084
	2013	14.72	28.98	18.70	727.55	697.96	1.48	78.82	808.00	0.217	0.087
	2014	15.17	31.51	19.99	773.19	779.52	2.21	81.45	880.00	0.209	0.140
	2015	15.47	34.10	20.88	770.42	862.52	2.40	82.60	835.50	0.186	0.101
Hebei	2006	68.98	10.30	146.18	611.04	389.54	1.91	217.94	3925.40	1.545	0.723
	2007	69.43	11.69	180.47	720.19	460.07	2.15	235.85	4803.60	1.492	0.623
	2008	69.89	13.44	203.46	870.13	527.60	2.06	243.22	3755.80	1.345	0.568
	2009	70.34	14.72	220.73	895.98	606.83	1.32	254.19	5077.90	1.253	0.519
	2010	71.94	16.26	256.28	1070.77	712.38	1.09	262.01	5632.40	1.234	0.500
	2011	72.41	18.29	290.57	1312.69	848.32	2.43	280.75	7718.49	1.412	1.322
	2012	72.88	20.54	318.67	1400.36	938.48	2.36	287.63	6764.74	1.341	1.236
	2013	73.33	22.23	338.20	1478.19	1027.91	5.12	296.64	7912.13	1.285	1.313
	2014	73.84	24.14	344.75	1501.29	1096.08	8.90	293.20	7273.23	1.190	1.798
	2015	74.25	26.15	343.95	1438.69	1197.98	5.42	293.95	7857.00	1.108	1.575

The units of S_1, S_2, and S_3–S_5 are million people, thousand yuan, and billion yuan, respectively. The units of E_1, E_2, E_3, E_4, and E_5 are billion yuan, million tons of standard coal equivalent, billion cubic meters, million tons, and million tons, respectively.

completed in the treatment of industrial pollution (E_1) is the single most important driving factor for the environment changes. Except total volume of sulfur dioxide emission (E_4) has a contribution share of 11%, the impacts of other 3 factors (E_2, E_3, and E_5) are negligible. For Tianjin, the environment changes derive mainly from treatment of industrial pollution (E_1), total energy consumption (E_2), total volume of industrial waste gas emission (E_3), and total volume of soot (dust) emission (E_5). Their contribution shares vary from 19% to 33%. The contribution share of sulfur dioxide emission (E_4) (4%) is obviously lower than the above 4 factors. Differing from Beijing and Tianjin, industrial pollution (E_1) and total volume of soot (dust) emission (E_5) contribute 85% of the environment changes. Besides, total volume of industrial waste gas emission (E_3) contributes 11%. Furthermore, if considered as a whole, the change in environmental level is mainly driven by treatment of industrial pollution (E_1) and total volume of soot (dust) emission (E_5). Although less important than E_1 and E_5, total volume of industrial waste gas emission (E_3) is also indispensable during the process of the environment changes.

4.2. Coupling Coordination Trend Analysis. Trends of socioeconomic development score (R_S), environmental pollution score (R_E), and coupling coordination degree (D) of the BTH region were fitted using the optimal estimated equations ($p = 2$) shown in Table 5. In Figures 2(a)–2(c), the central solid line is the fitting trend to the abovementioned indicators, and the dashed lines above and below it are the ±10% deviation boundaries to the fitting results. Moreover, the difference of socioeconomic development and environmental pollution scores (RS - RE) and its fitting curve are listed in Figure 2(d).

Figures 2(a)–2(c) show that socioeconomic development score, environmental pollution score, and coupling coordination degree all present rising trends. The social economy

Table 3: Evaluation weight for each indicator in each region.

Region	S_1	S_2	S_3	S_4	S_5	E_1	E_2	E_3	E_4	E_5
Beijing	3.23	28.65	11.32	19.64	37.16	82.90	0.83	2.93	10.59	2.76
Tianjin	3.04	14.03	11.15	27.64	44.14	19.28	24.60	18.65	4.31	33.16
Hebei	0.18	23.07	20.06	23.22	33.47	50.23	1.72	11.47	1.61	34.97
BTH	0.68	22.60	18.05	23.67	35.00	35.07	3.31	13.57	2.79	45.27

The unit is %.

Table 4: Socio-economic development and environmental pollution scores and coupling coordination degree for each region in each year.

Year	Beijing			Tianjin			Hebei			BTH		
	$R_{S,B}$	$R_{E,B}$	D_B	$R_{S,T}$	$R_{E,T}$	D_T	$R_{S,H}$	$R_{E,H}$	D_H	R_S	R_E	D
2006	0.059	0.052	0.235	0.048	0.091	0.257	0.054	0.094	0.267	0.053	0.086	0.260
2007	0.068	0.057	0.250	0.055	0.087	0.263	0.064	0.086	0.272	0.063	0.083	0.269
2008	0.076	0.055	0.254	0.068	0.086	0.276	0.074	0.084	0.281	0.073	0.078	0.275
2009	0.082	0.102	0.302	0.076	0.087	0.285	0.080	0.115	0.310	0.080	0.089	0.291
2010	0.092	0.168	0.353	0.090	0.091	0.301	0.093	0.134	0.335	0.093	0.099	0.309
2011	0.104	0.284	0.415	0.107	0.103	0.324	0.109	0.110	0.331	0.108	0.121	0.338
2012	0.114	0.104	0.331	0.121	0.112	0.342	0.120	0.106	0.336	0.119	0.117	0.344
2013	0.126	0.083	0.320	0.134	0.109	0.348	0.129	0.085	0.324	0.129	0.104	0.340
2014	0.134	0.052	0.290	0.146	0.126	0.368	0.136	0.091	0.334	0.137	0.114	0.354
2015	0.146	0.042	0.280	0.155	0.108	0.360	0.141	0.093	0.338	0.145	0.109	0.355

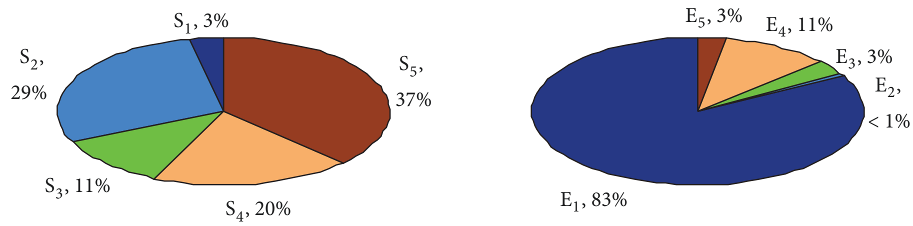
Table 5: Fitting equation parameters and AIC and SC results for socio-economic development and environmental pollution scores and coupling coordination degree of the BTH region.

Explained variable	p	Estimated parameters	AIC	SC
R_S	2	$[0.05291\ \ 0.00534\ \ 0.00046]$	2.88e-005	3.06e-005
	3	$[0.06229\ \ 0.00336\ \ 0.00029\ \ 0.00003]$	9.76e-005	1.07e-004
R_E	2	$[0.08244\ \ 0.00204\ \ 0.00016]$	1.33e-004	1.41e-004
	3	$[0.08513\ \ 0.00138\ \ 0.00011\ \ 0.00001]$	1.81e-004	1.98e-004
D	2	$[0.26062\ \ 0.00605\ \ 0.00051]$	1.90e-004	2.02e-004
	3	$[0.27965\ \ 0.00313\ \ 0.00025\ \ 0.00002]$	4.68e-004	5.12e-004

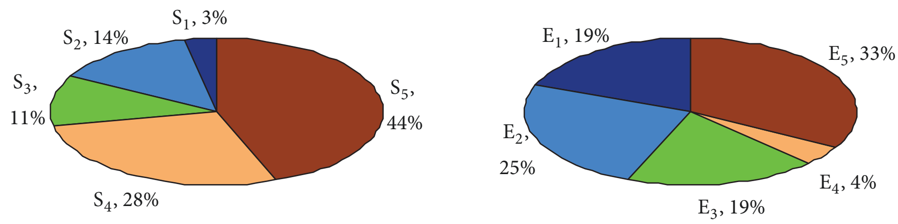
was developed at the expense of environmental pollution. Figure 2(d) shows that the score difference is larger than 0 since 2012. This means that the dependence of socioeconomic developed on environmental pollution weakened since that year. The Chinese government advocated the economic transition from extensive to intensive since the late 1990s and adhered to this development direction for over 20 years. The above results confirm the transition effect. Furthermore, the rising trend of the coupling coordination degree indicates that the BTH region still has huge potential to improve the local environment. If the BTH governments are not satisfied with the environmental quality, they can sacrifice part of the economic growth in exchange for a better environment.

4.3. Outlier Analysis. As shown in Figure 2(c), the coupling coordination degree of 2011 differs from its neighbors, and should be considered an outlier. According to the fitting results of Figures 2(a) and 2(b), this outlier comes from abnormally severe environmental pollution. As shown in the environmental pollution data in Table 2, it is easy to find that severe environmental pollution in 2011 mainly comes from huge energy consumption and energy-related pollution emissions from Hebei. Figure 3 shows the energy consumption (unit: million tons of standard coal equivalent) of each sector in Hebei during 2006–2015.

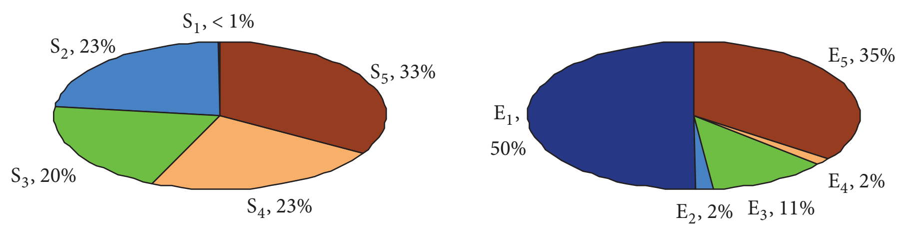
As shown in Figure 3, the secondary industry has always been the most important energy consumer in Hebei. During 2006–2015, its energy consumption share as high as 80.14% [5]. As the leading steal producing province in China, the smelting and pressing of ferrous metals sector consumed a considerable amount of energy in the secondary industry of Hebei (43.61% in 2006–2015) [1, 5]. In 2011, to support the large-scale construction of infrastructure and real estate in China, and also because the provincial government of Hebei has not strictly limited the development of building material



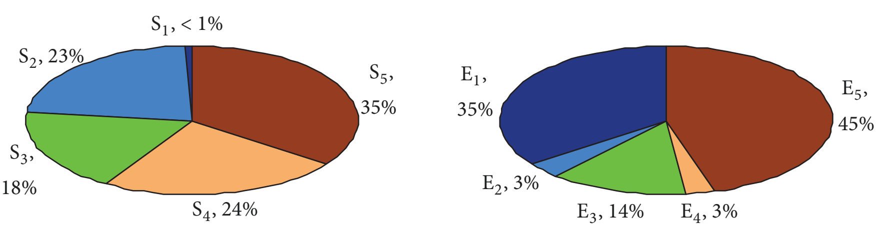
(a) Beijing



(b) Tianjin



(c) Hebei



(d) BTH

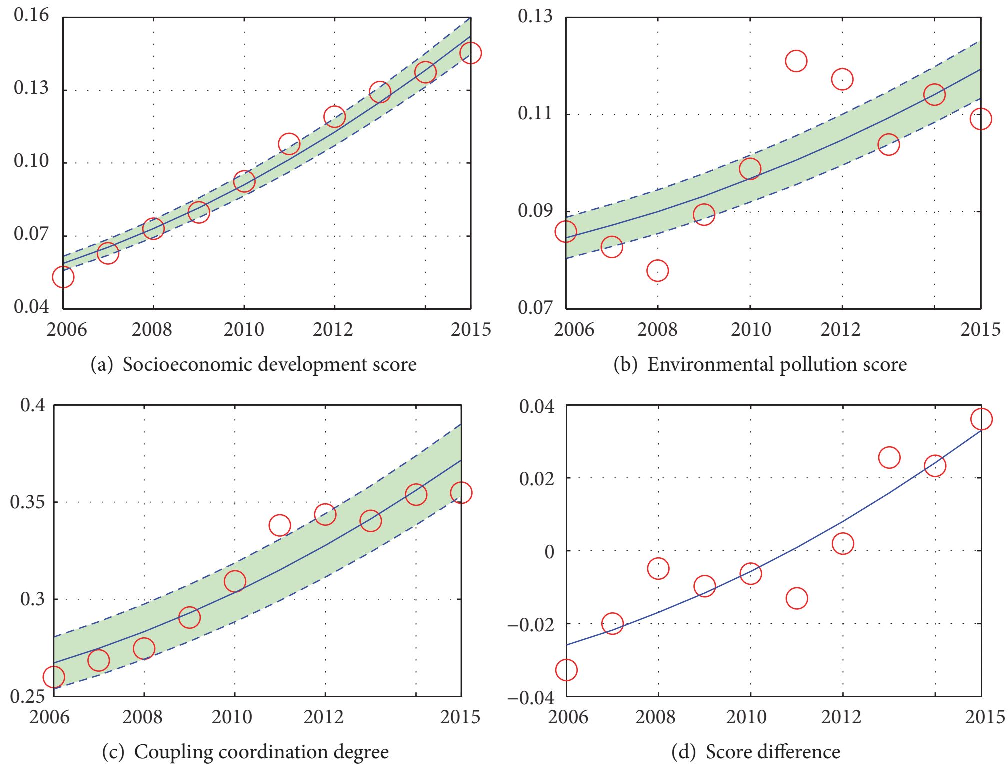
Figure 1: Pie charts of indicator weights for socioeconomic development and environmental pollution in each region.

sectors at that time, the smelting and pressing of ferrous metals and other related sectors went through an extraordinary growth, which led to a sheer increase in energy consumption. In fact, besides the smelting and pressing of ferrous metals, output and energy consumption of other building material sectors (e.g., cement) also greatly increased [5]. As the consumption share of fossil energy in the total energy sources was not less than 98.14% at that time, the abovementioned energy consumption increase emitted significantly more pollutants and aggravated the local environment [35]. Until 2 years later in 2013, the Hebei provincial government began to increase the investment in the treatment of industrial pollution and limited the development of these sectors and then mitigated the environmental pollution.

5. Conclusions

As one of the most important urban agglomerations of China, the BTH region has been suffering severe environmental pollution. To guide the sustainable development of this region, this research used an entropy-based coupling coordination degree model to measure the coupling relationship between socioeconomic development and environmental pollution. The research also used a polynomial equation with PLS algorithm to fit the above relationship during 2006–2015. The empirical analyses drew the following implications for the socioeconomic and environmental policy adjustments of the BTH region.

(1) Beijing, Tianjin, and Hebei presented similar socioeconomic development modes. In general, the gross product of the tertiary industry is the most important driver of socioeconomic development. The contributions of annual disposable income per capita of urban households, gross product of primary industry, and gross product of the secondary industry were close, and the impact of resident population was negligible. Contrary to the socioeconomic development mode, the environmental pollution of the



(a) Socioeconomic development score
(b) Environmental pollution score
(c) Coupling coordination degree
(d) Score difference

Figure 2: Fitting results to socioeconomic development score, environmental pollution score, coupling coordination degree, and score difference of the BTH region.

three regions was different. Change in Beijing's environment nearly only depended on the investment completed in the treatment of industrial pollution. Besides this factor, soot (dust) emissions were also important for the environmental level of Hebei. As to Tianjin, the above two factors, total energy consumption, and industrial waste gas emission were all important.

(2) The social economy of the BTH region has been developing at the expense of the environment. During 2006–2015, the social economy developed, yet the environment deteriorated. As socioeconomic development was faster than that of environmental deterioration, the environmental cost of socioeconomic development decreased year by year.

(3) At present, the BTH region still possesses huge potential to improve the local environment. The social economy of the BTH region developed fast, although the environment was severely polluted. If the BTH governments are willing to accept a lower socioeconomic development target, environmental pollution will be effectively mitigated.

(4) Compared with Beijing and Hebei, the contribution of investment completed in the treatment of industrial pollution in Tianjin was obviously less. Tianjin should therefore increase investment in this area. Moreover, the soot (dust) emissions in Tianjin and Hebei greatly contributed to environmental deterioration and should then be strictly controlled.

(5) Energy-related pollutants emitted by the smelting and pressing of ferrous metals and other building material sectors in Hebei have significant impact on environmental quality in the BTH region. Development of these sectors should be strictly limited.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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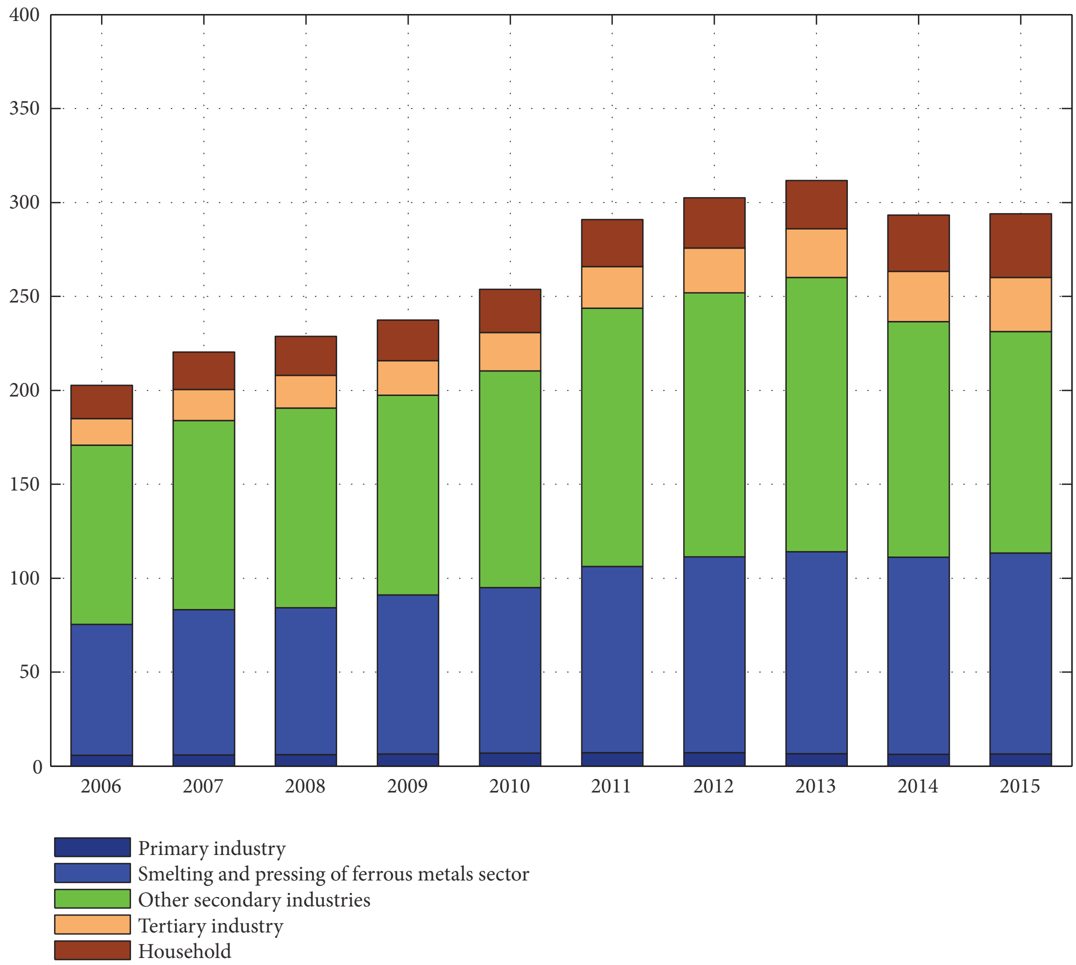

Figure 3: Energy consumption of each sector in Hebei during 2006–2015.

References

[1] National Bureau of Statistics of the People's Republic of China, *China Statistic Yearbook 2007-2016*, China Statistics Press, China, 2016, http://www.stats.gov.cn/tjsj/ndsj/.

[2] Ministry of Ecology and Environment, *Air Quality Conditions of The Country in The First Half of 2018*, 2018, http://www.mee.gov.cn/gkml/sthjbgw/qt/201807/t20180722_447072.htm.

[3] Beijing Municipal Bureau of Statistics, *Beijing Statistical Yearbook 2015-2016*, China Statistics Press, China, 2016, http://www.bjstats.gov.cn/tjsj/.

[4] Tianjin Municipal Bureau of Statistics, *Tianjin Statistical Yearbook 2009-2016*, China Statistics Press, China, 2016, http://stats.tj.gov.cn/Category_29/Index.aspx.

[5] Hebei Provincial Bureau of Statistics, *Hebei Economic Yearbook 2016*, China Statistics Press, China, 2016, http://www.hetj.gov.cn/res/nj2016/indexch.htm.

[6] ADB (Asian Development Bank), "Strategic framework for environmental protection," in *Toward an Environmentally Sustainable Future: Country Environmental Analysis of the People's Republic of China*, Q. F. Zhang and R. Crooks, Eds., pp. 124–148, Metro Manila, Philippines, 2012.

[7] J. Li, L. Chen, Y. Xiang, and M. Xu, "Research on influential factors of PM2.5 within the Beijing-Tianjin-Hebei Region in China," *Discrete Dynamics in Nature and Society*, vol. 2018, Article ID 6375391, 10 pages, 2018.

[8] Z. Zhang, Y. Hao, and Z.-N. Lu, "Does environmental pollution affect labor supply? An empirical analysis based on 112 cities in China," *Journal of Cleaner Production*, vol. 190, pp. 378–387, 2018.

[9] L. Zhu, Q. Gan, Y. Liu, and Z. Yan, "The impact of foreign direct investment on SO2 emissions in the Beijing-Tianjin-Hebei region: a spatial econometric analysis," *Journal of Cleaner Production*, vol. 166, pp. 189–196, 2017.

[10] J. Gao, K. Wang, Y. Wang et al., "Temporal-spatial characteristics and source apportionment of PM2.5 as well as its associated chemical species in the Beijing-Tianjin-Hebei region of China," *Environmental Pollution*, vol. 233, pp. 714–724, 2018.

[11] L. Wang, P. Li, S. Yu et al., "Predicted impact of thermal power generation emission control measures in the Beijing-Tianjin-Hebei region on air pollution over Beijing, China," *Scientific Reports*, vol. 8, no. 1, p. 934, 2018.

[12] H. Wang and L. Zhao, "A joint prevention and control mechanism for air pollution in the Beijing-Tianjin-Hebei region in china based on long-term and massive data mining of pollutant concentration," *Atmospheric Environment*, vol. 174, pp. 25–42, 2018.

[13] Y. Zhang, J. Shen, F. Ding, Y. Li, and L. He, "Vulnerability assessment of atmospheric environment driven by human impacts," *Science of the Total Environment*, vol. 571, pp. 778–790, 2016.

[14] C. Fang, K. Luo, Y. Kong, H. Lin, and Y. Ren, "Evaluating performance and elucidating the mechanisms of collaborative development within the Beijing–Tianjin–Hebei region, China," *Sustainability*, vol. 10, no. 2, p. 471, 2018.

[15] S. Kuznets, "Economic growth and income inequality," *American Economic Review*, vol. 49, pp. 1–28, 1955.

[16] G. M. Grossman and A. B. Krueger, "Environmental impacts of a north american free trade agreement," National Bureau of Economic Research Working Paper Series 3914, 1991.

[17] G. M. Grossman and A. B. Krueger, "Economic growth and the environment," *The Quarterly Journal of Economics*, vol. 110, no. 2, pp. 353–377, 1995.

[18] T. Panayotou, "Empirical tests and policy analysis of environmental degradation at different stages of economic development," in *Working Paper, Technology and Employment Programme*, International Labor Office, Geneva, Switzerland, 1993, http://www.econis.eu/PPNSET?PPN=258294558.

[19] A. Sinha and M. Shahbaz, "Estimation of environmental Kuznets Curve for CO2 emission: role of renewable energy generation in India," *Journal of Renewable Energy*, vol. 119, pp. 703–711, 2018.

[20] S. A. Sarkodie, "The invisible hand and EKC hypothesis: what are the drivers of environmental degradation and pollution in Africa?" *Environmental Science and Pollution Research*, vol. 25, no. 22, pp. 21993–22022, 2018.

[21] L. Shen, Y. Huang, Z. Huang, Y. Lou, G. Ye, and S.-W. Wong, "Improved coupling analysis on the coordination between socio-economy and carbon emission," *Ecological Indicators*, vol. 94, pp. 357–366, 2018.

[22] Y. Hao, Y. Liu, J.-H. Weng, and Y. Gao, "Does the Environmental Kuznets Curve for coal consumption in China exist? New evidence from spatial econometric analysis," *Energy*, vol. 114, pp. 1214–1223, 2016.

[23] S. A. Sarkodie and V. Strezov, "Effect of foreign direct investments, economic development and energy consumption on greenhouse gas emissions in developing countries," *Science of the Total Environment*, vol. 646, pp. 862–871, 2019.

[24] Z. Wang and X. Ye, "Re-examining environmental Kuznets curve for China's city-level carbon dioxide (CO2) emissions," *Spatial Statistics*, vol. 21, no. part B, pp. 377–389, 2017.

[25] T. Xu, "Investigating Environmental Kuznets Curve in China–Aggregation bias and policy implications," *Energy Policy*, vol. 114, pp. 315–322, 2018.

[26] Y. Wang, Z. Zhang, and H. Sun, "Assessing customer satisfaction of urban rail transit network in Tianjin based on intuitionistic fuzzy group decision model," *Discrete Dynamics in Nature and Society*, vol. 2018, Article ID 4205136, 11 pages, 2018.

[27] J. He, S. Wang, Y. Liu, H. Ma, and Q. Liu, "Examining the relationship between urbanization and the eco-environment using a coupling analysis: Case study of Shanghai, China," *Ecological Indicators*, vol. 77, pp. 185–193, 2017.

[28] H. I. Choi and H. P. Moon, "Weierstrass-type approximation theorems with Pythagorean hodograph curves," *Computer Aided Geometric Design*, vol. 25, no. 4-5, pp. 305–319, 2008.

[29] M. Meng, S. Mander, X. Zhao, and D. Niu, "Have market-oriented reforms improved the electricity generation efficiency of China's thermal power industry? An empirical analysis," *Energy*, vol. 114, pp. 734–741, 2016.

[30] X. Bry, C. Trottier, T. Verron, and F. Mortier, "Supervised component generalized linear regression using a PLS-extension of the Fisher scoring algorithm," *Journal of Multivariate Analysis*, vol. 119, pp. 47–60, 2013.

[31] M. Meng and D. Niu, "Annual electricity consumption analysis and forecasting of China based on few observations methods," *Energy Conversion and Management*, vol. 52, no. 2, pp. 953–957, 2011.

[32] National Bureau of Statistics, *China Statistical Yearbook on Environment*, China Statistics Press, China, 2017.

[33] W. Sun and J. Sun, "Prediction of carbon dioxide emissions based on principal component analysis with regularized extreme learning machine: the case of China," *Environmental Engineering Research*, vol. 22, no. 3, pp. 302–311, 2017.

[34] P. Fan, Z. Ouyang, C. Basnou, J. Pino, H. Park, and J. Chen, "Nature-based solutions for urban landscapes under post-industrialization and globalization: Barcelona versus Shanghai," *Environmental Research*, vol. 156, pp. 272–283, 2017.

[35] M. Meng, Y. Fu, and X. Wang, "Decoupling, decomposition and forecasting analysis of China's fossil energy consumption from industrial output," *Journal of Cleaner Production*, vol. 177, pp. 752–759, 2018.