Characterization of Green Development Level Measurement and Spatial and Temporal Evolution of Beijing-Tianjin-Hebei Cities under the "Dual Carbon" Goal

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Abstract. This paper takes 13 prefectural-level cities in Beijing-Tianjin-Hebei as research samples, constructs a green development evaluation index system for urban agglomerations from the four dimensions of scientific and technological innovation, economic growth, green life and green "double carbon", and applies the entropy value method, ArcGIS natural fracture classification method and other tools to measure the level of green development from 2011-2020 and analyze its spatial and temporal evolution characteristics.Using the entropy value method, ArcGIS natural fracture classification method and other tools, we measured the level of green development from 2011 to 2020 and analyzed its spatial and temporal evolution characteristics.The study found that: (1) in the evaluation system, scientific and technological innovation, green "double carbon" and economic growth have the highest weight on the level of green development; (2) the average growth rate of the level of green development in Beijing-Tianjin-Hebei cities was 6.75% in 2011-2015, and it rose to 8.88% in 2016-2020; (3) the level of green development in the Beijing-Tianjin-Hebei(3) Beijing-Tianjin-Hebei city cluster gradually forms a spatial distribution pattern of "high - high agglomeration, low - low agglomeration".

Keywords: Green development; peak carbon dioxide emissions; carbon neutrality;time-space evolution.

1. Introduction

The Fifth Plenary Session of the 18th CPC Central Committee included "green development" in the five concepts of economic and social development for the first time, and the Sixth Plenary Session of the 19th CPC Central Committee further clarified that we need to consciously practice green, recycling, and low-carbon development paths, and adhere to the path of civilized development of development of production, affluent living, and ecological well-being, and green development has thus become the core orientation of China's long-term development.

In September 2020, President Xi Jinping announced at the United Nations General Assembly that China would achieve carbon neutrality by 2060, and the "dual-carbon" strategy has become an important engine for promoting the green transformation of the economy.As one of China's three major urban agglomerations, the Beijing-Tianjin-Hebei region, with its concentrated energy consumption, accounts for 11% of the country's total carbon emissions, and its emission intensity is 40% higher than the national average[1], and thus plays a key role in the promotion of the "dual-carbon" goal.Therefore, clarifying the new connotation of green development in Beijing-Tianjin-Hebei, proposing synergistic emission reduction measures, and objectively assessing the level of green development in the cities are of great significance in narrowing the regional gap and improving the quality of synergistic development..

To grasp the new connotation of Beijing-Tianjin-Hebei coordinated development, propose synergetic measures for "dual carbon" promotion, and objectively evaluate urban green development levels, it is essential to analyze regional differences and their evolution trends. This will help improve overall green development, narrow regional gaps, and contribute to high-quality coordinated development and regional green cooperation.

2. Literature References

The conceptual origins of green development can be traced to the 19th century, when Marx and Engels proposed a scientific view of nature [2], laying an early theoretical foundation. Later scholars such as Meadows, Boulding, and Daley expanded on this from perspectives like low-carbon constraints, ecological homeostasis, and sustainability, enriching the theoretical system of green development [3-5]. Green development is both a process of building ecological civilization in economic activities [6] and a new lifestyle that balances economic-societal progress with ecological protection, aiming to achieve human-nature harmony and comprehensive human development [7-9].

Internationally, the UN Environment Programme has launched Green New Deal and Green Economy initiatives [10]; the U.S. has invested in clean energy to drive green growth; the EU has focused on green industries; South Korea has adopted green growth strategies; and Japan has promoted a low-carbon society [11-12].

In terms of evaluation indices, institutions like the UNEP, OECD, World Bank, and Global Green Growth Institute have developed frameworks covering economic-societal development, resource utilization, environmental protection, and policy systems [13-16]. Since the 21st century, Chinese scholars have expanded these frameworks by incorporating green innovation [18], green equity [19], and organizational culture [20]. For example, Xiong Xi et al. (2019) constructed an evaluation system for the Bohai Rim region based on green ecology, life, and production [26]; Zhang Naiming et al. designed indices for Yunnan's counties focusing on ecological optimization and economic development [27]; and Yuan Wenhua et al. built a system for Shandong cities from urban support and coordination perspectives [28].

Geographically, research has expanded from single cities to urban agglomerations and nations. Pei Xiao et al. studied the coupling of green development and digital economy in the Yangtze River Economic Belt [29]; Wu Caixia assessed low-carbon levels in Belt and Road countries [30]; and Gao Ying analyzed green development differences in the Yellow River Basin [31]. The Beijing-Tianjin-Hebei urban agglomeration, as China's third economic pole, has attracted increasing attention.

Methodologically, studies have used mathematical statistics [33], ML indices [34], LMDI models [35], entropy methods [36-37], and spatial measurement models [52]. However, existing research on Beijing-Tianjin-Hebei mostly focuses on tourism [56], agriculture [57], and industry [58], with limited exploration of prefecture-level cities' green development, few studies incorporating "dual carbon" indicators, and insufficient spatial-temporal analysis. This paper addresses these gaps by adding "dual carbon" indices and using entropy and ArcGIS methods to analyze 2011-2020 data.

3. Research methodology, data sources, and indicator system

3.1 Research Methodology

This paper uses the entropy method to objectively evaluate green development levels. The core principle is that an indicator's weight is determined by its information content: greater variation indicates more information, lower entropy, and higher weight. The calculation steps are:

Step 1: Indicator standardization processing.

$$\begin{cases} \text{Positive indicators:} \quad X_{ijt}^{+} = \dfrac{X_{ijt} - \min x_j}{\max x_j - \min x_j} \\ \text{Negative indicators:} \quad X_{ijt}^{-} = \dfrac{\max x_j - X_{ijt}}{\max x_j - \min x_j} \end{cases} \tag{1}$$

In equation (1), a positive indicator, i.e., the higher the value of the indicator, the better, and a negative indicator, i.e., the lower the value of the indicator, the better, i indicates city $(i = 1, 2, \cdots, n)$;

j indicates indicator $(j=1,2,\cdots,m)$; t indicates year $(t=1,2\cdots,k)$; X_{ijt} is the original value of the t year of the j indicator of city i; X_{ijt}^{+} and X_{ijt}^{-} is the standardized value; to make the data processing meaningful, it is necessary to eliminate the zero value appearing in the standardized data, so the standardized data will be shifted by 0.0001 as a whole. and $\min x_j$ 、 $\max x_j$ indicates the maximum and minimum values in the j indicator.

The second step is to calculate the share of city i's indicator j in the year t in the sum of the indicator j:

$$P_{ijt}=\frac{X_{ijt}^{\pm}}{\sum_{t=1}^{k}\sum_{i=1}^{n}X_{ijt}^{\pm}} \quad (2)$$

The third step is to calculate the information entropy:

$$e_j=-\frac{1}{\ln(kn)}\sum_{t=1}^{k}\sum_{i=1}^{n}(P_{ijt}\times\ln P_{ijt}),(0\le e_j\le 1) \quad (3)$$

The fourth step is to calculate the coefficient of variation g_j and indicator weights w_j for each indicator:

$$g_j=1-e_j \quad (4)$$

$$w_j=\frac{g_j}{\sum_{j=1}^{m}g_j} \quad (5)$$

The fifth step is to calculate the composite score for the city i in a year t:

$$D_{it}=\sum_{j=1}^{m}X_{ijt}w_j \quad (6)$$

3.2 Construction of Evaluation Indicator System for Green Development Level of Beijing-Tianjin-Hebei City Cluster

The measurement of green development level is a comprehensive evaluation of the actual situation of a city's economy, ecology, and society. Domestic scholars tend to build evaluation index systems based on the national or economic belt level, which needs to further explore the actual green development level of the Beijing-Tianjin-Hebei urban agglomeration under the background of carbon peak and carbon neutrality. Therefore, based on existing research results, this paper refers to the Green Development Indicator System jointly formulated by the National Development and Reform Commission and other departments in 2016 and the China Carbon Neutral Development Report (2022), and adds carbon reduction indicators such as forest coverage rate and air quality excellent rate, as well as carbon increase indicators such as cement output and crude steel output. More attention is paid to highlighting the green development characteristics of urban space and the scientificity, systematicness, and balance of indicator selection. As shown in Table 1.

Table 1. Beijing-Tianjin-Hebei City Cluster Green Development Level Evaluation Index system

Target Level	System Level	Indicator Layer	Causality	Weights
Green development	Technological Innovation(35.79%)	Number of R&D units in industrial enterprises above designated size (units)	Positive	9.456%

		Number of R&D personnel in industrial enterprises above designated size (persons)	Positive	8.433%
		Internal Expenditures on R&D Funding for Industrial Enterprises Above Scale (RMB 10,000,000)	Positive	9.473%
		Number of patent applications by industrial enterprises above designated size (pieces)	Positive	8.431%
	Economic Growth(21.76%)	GDP per capita (yuan per person)	Positive	3.456%
		Per capita disposable income of urban residents (yuan per person)	Positive	2.573%
		Total retail sales of consumer goods (billions of dollars)	Positive	8.499%
		Growth rate of investment in fixed assets (%)	Positive	1.032%
		Industrial value added as a share of GDP (%)	Positive	1.339%
		Value added of the secondary sector as a share of GDP (%)	Negative	1.874%
		Value added of the tertiary sector as a share of GDP (%)	Positive	2.991%
	Green Living(17.21%)	Population density (persons/km2)	Negative	1.244%
		Green area of parks (ha)	Positive	10.516%
		Greening coverage of built-up areas (%)	Positive	1.307%
		Per capita daily domestic water consumption (liters)	Negative	1.865%
		Sewage treatment rate (%)	Positive	0.765%
		Average regional ambient noise dB(A)	Negative	0.523%
		Average value of ambient traffic noise dB(A)	Negative	0.99%
	Green "Double Carbon"(25.23%)	Forest cover (%)	Positive	1.609%
		Rate of non-hazardous treatment of municipal domestic waste (%)	Positive	0.229%
		Total number of public bus and tram passengers (10,000)	Positive	18.46%
		Cement production (million tons)	Negative	0.556%
		Crude steel production (million tons)	Negative	0.567%
		Electricity generation (billion kWh)	Negative	1.122%
		Annual hours of sunshine (hours)	Positive	0.662%
		Air quality excellence rate (%)	Positive	1.323%
		Industrial sulfur dioxide emissions (tons)	Negative	0.705%

3.3 Data sources

This paper analyzes the green development level of 13 cities in the Beijing-Tianjin-Hebei region from 2011 to 2020. The original statistical data are mainly from the China Statistical Yearbook,

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China Urban Statistical Yearbook, China Urban Construction Yearbook, China Environmental Statistical Yearbook, China Regional Economic Statistical Yearbook, Beijing Statistical Yearbook, Tianjin Statistical Yearbook, Hebei Economic Yearbook, municipal statistical yearbooks, as well as the national economic and social development statistical bulletins, environmental quality bulletins, and official websites of statistics bureaus of various cities in Beijing-Tianjin-Hebei. Among them, the proportion of industrial added value in GDP and the air quality excellent rate are obtained through calculation. Missing data are supplemented by interpolation to ensure scientific validity.

4. Analysis of results

4.1 Characteristics of time-series evolution of green development level in Beijing-Tianjin-Hebei urban agglomeration

This paper takes the data of 27 indicators of 13 cities in Beijing-Tianjin-Hebei from 2011 to 2020 as samples, and uses the above-mentioned entropy value method to calculate the weights of secondary and tertiary indicators (see Table 1). The weight ranking of each system level is: scientific and technological innovation > green "dual carbon" > economic growth > green life. The Beijing-Tianjin-Hebei region is the economic core area of the three northern provinces and an important engine of China's scientific and technological innovation. Promoting the coordinated development of Beijing-Tianjin-Hebei and building the core position of scientific and technological innovation in the Beijing-Tianjin-Hebei region is a major strategic plan of the Party Central Committee with Comrade Xi Jinping as the core to comprehensively deepen reform and expand opening up in the new era [59]. With the establishment of the "dual-carbon" goal, Beijing-Tianjin-Hebei has become a key region for the implementation of the "carbon peak" and "carbon neutral" goals. Therefore, scientific and technological innovation, green "dual-carbon" and economic growth account for a relatively high proportion in green development.

From 2011 to 2020, the green development index of Beijing-Tianjin-Hebei cities (see Table 2) shows that the green development level generally presents a fluctuating upward trend, with average values of 0.307, 0.411, 0.536, and 0.725 in 2011, 2014, 2017, and 2020 respectively. On the whole, Beijing has always been in the leading position, followed by Tianjin, while some cities in Hebei have relatively low green development levels.

Table 2. Beijing-Tianjin-Hebei Cities Green Development Index, 2011-2020

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Mean Value
Beijing	0.433	0.476	0.417	0.571	0.592	0.606	0.643	0.664	0.681	0.825	0.591
Tianjin	0.316	0.394	0.447	0.548	0.553	0.619	0.595	0.543	0.538	0.800	0.535
Shijiazhuang	0.327	0.349	0.341	0.433	0.451	0.516	0.635	0.614	0.655	0.777	0.510
Tangshan	0.318	0.321	0.313	0.518	0.412	0.417	0.520	0.541	0.565	0.599	0.452
Qinhuangdao	0.361	0.356	0.342	0.534	0.431	0.412	0.475	0.529	0.525	0.569	0.454

Handan	0.272	0.286	0.285	0.310	0.363	0.427	0.480	0.538	0.610	0.766	0.434
Xingtai	0.239	0.235	0.244	0.314	0.391	0.437	0.533	0.638	0.710	0.756	0.450
Baoding	0.320	0.282	0.315	0.401	0.419	0.434	0.533	0.598	0.562	0.744	0.461
Zhangjiakou	0.235	0.318	0.352	0.389	0.412	0.472	0.455	0.526	0.515	0.699	0.437
Chengde	0.310	0.393	0.407	0.440	0.467	0.512	0.567	0.532	0.577	0.677	0.488
Cangzhou	0.293	0.280	0.303	0.338	0.362	0.414	0.468	0.541	0.666	0.735	0.440
Langfang	0.312	0.253	0.221	0.249	0.343	0.438	0.500	0.602	0.635	0.778	0.433
Hengshui	0.254	0.299	0.310	0.298	0.338	0.454	0.562	0.654	0.671	0.698	0.454
Mean Value	0.307	0.326	0.331	0.411	0.426	0.474	0.536	0.578	0.608	0.725	

The average growth rate of green development level of Beijing-Tianjin-Hebei cities from 2011 to 2015 was 6.75%. During this period, the role of economic stimulus had an impact on the ecological environment of the urban agglomeration. The overall pollution emission in the Beijing-Tianjin-Hebei region was relatively high, and the cost of environmental damage directly affected the green development of the region, resulting in a slow growth rate of green development level. In 2010, the Ministry of Environmental Protection and other nine departments issued the "Guiding Opinions on Promoting Joint Prevention and Control of Air Pollution and Improving Regional Air Quality" to promote the green development of Beijing-Tianjin-Hebei cities, which put forward the concept of "joint prevention and control" and pointed out that the key areas for joint prevention and control of air pollution are Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta. In 2013, the Ministry of Environmental Protection and other three departments issued the "Implementation Rules for the Air Pollution Prevention and Control Action Plan in Beijing-Tianjin-Hebei and Surrounding Areas" to further establish and improve the regional coordination mechanism for green development of Beijing-Tianjin-Hebei cities. This has led to a significant improvement in the green development level of Beijing-Tianjin-Hebei cities. The proposal of the Beijing-Tianjin-Hebei Coordinated Development Strategy in 2014 promoted the rise of green development level and accelerated the synchronized progress of economic development and ecological environment construction in the region.

In 2017, the Development and Reform Commissions of Beijing, Tianjin, and Hebei jointly issued the Beijing-Tianjin-Hebei Energy Coordinated Development Action Plan (2017-2020), which provided a clear action plan for jointly improving the energy governance and management level of Beijing-Tianjin-Hebei cities. Therefore, the green development level of Beijing-Tianjin-Hebei cities continued to rise after 2016. The average growth rate of green development level of Beijing-Tianjin-Hebei cities from 2016 to 2020 was 8.88%, an increase of 2.13 percentage points compared with 2011-2015. During this period, the tertiary industry in Tianjin and Hebei developed rapidly, which promoted economic growth while reducing environmental costs. During this period, governments in the region worked together to promote the coordinated ecological and environmental governance of Beijing-Tianjin-Hebei, replacing the concept of only pursuing GDP with the goals of environmental protection and people's well-being, and achieved remarkable results in ecological and environmental governance.

4.2 Characteristics of the spatial evolution of green development level in the Beijing-Tianjin-Hebei city cluster

To observe the dynamic evolution law of the green development level of Beijing-Tianjin-Hebei cities over time, according to the measurement results obtained by the entropy value method, this paper further divides the urban green development level into four levels: high, higher, lower, and low by using the natural fracture classification method of ArcGIS software, and the figure distinguishes the changes in the green development level of Beijing-Tianjin-Hebei cities by color. As shown in Figure 1.

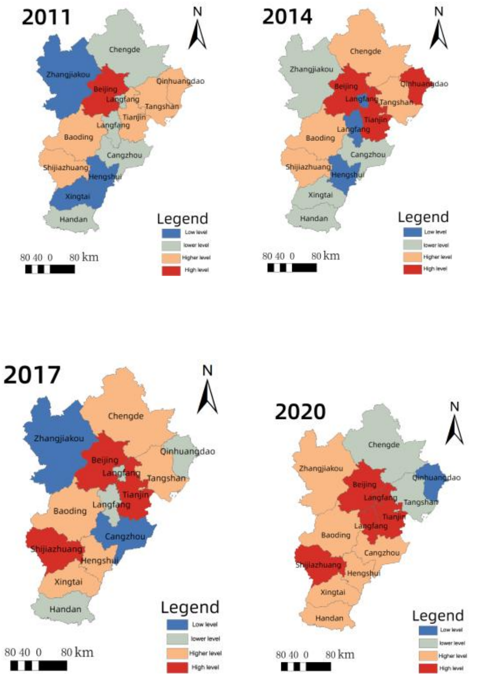

Figure. 1 Grading of green development levels in Beijing-Tianjin-Hebei cities, 2011, 2014, 2017 and 2020

In terms of quantitative changes, the number of cities with higher green development levels increased from 6 in 2011 to 10 in 2020; the number of cities with lower green development levels decreased from 7 in 2011 to 3 in 2020; and the number of cities with lower green development levels in 2011, 2014, 2017, and 2020 was 3, 2, 2, and 1 respectively. On the whole, from 2011 to 2020, the green development level of Beijing-Tianjin-Hebei cities has gradually improved, with the number of cities with higher green development levels increasing and the number of cities with lower green development levels decreasing.

From the perspective of regional distribution, from 2011 to 2020, although the distribution of green development levels of Beijing-Tianjin-Hebei cities has changed slightly, there are obvious differences in the green development levels of cities in different regions. In the Beijing-Tianjin-Hebei region, the green development level of Beijing has always been at the highest level; cities such as Tianjin, Zhangjiakou, Xingtai, Handan, Baoding, Shijiazhuang, Cangzhou, Langfang, and Hengshui have relatively high green development levels; while the green development level of cities such as Qinhuangdao and Tangshan is slightly lower.

The reasons for the differences in green development levels are as follows: First, Beijing and Tianjin currently have obvious advantages over Hebei in economic development, residents' income, green infrastructure construction, and resource endowment. The positive indicator values in these aspects contribute more to the green development level of Beijing and Tianjin, so these two cities, especially Beijing, have always maintained a high green development level. In addition, Beijing is positioned as a center of politics, culture, scientific and technological innovation, and international communication, focusing on the development of culture, education, tourism, science, and technology, while Tianjin focuses on the development of port economy, logistics, and high-end manufacturing. Due to the different functional orientations of the two cities, Tianjin's green development level is slightly lower than that of Beijing, basically at a higher green development level.

Second, in recent years, Zhangjiakou has focused on building an ecological barrier between Beijing and Tianjin, with low development intensity, and has traditional advantages in resource endowment and green services, so its overall green level is relatively high. From 2011 to 2020, especially since the 18th National Congress of the Communist Party of China, the ecological civilization construction of Shijiazhuang, Baoding, Cangzhou, Langfang, Hengshui, Xingtai, and Handan has been continuously strengthened. Relying on the geographical advantages of mountainous and plain areas, these cities have actively built a green, low-carbon, and circular industrial system, and their green development levels have been continuously improved. However, it should also be noted that in the industrial structure of Shijiazhuang, Hengshui, Xingtai, Handan, and other cities, the proportion of traditional resource-intensive industries such as iron and steel and coal chemical industry is relatively large, and these cities still face resource and environmental pressures.

Finally, Qinhuangdao and Tangshan are traditional and emerging industrial bases in the Beijing-Tianjin-Hebei region, with high pollutant emissions, energy consumption, and electricity consumption, so these cities have the lowest green development level.

5. Conclusions and recommendations

5.1 Conclusions

This paper constructs a green development evaluation index system for the Beijing-Tianjin-Hebei urban agglomeration from four dimensions: scientific and technological innovation, economic growth, green life, and green "dual carbon". It uses the entropy value method to measure the green development index from 2011 to 2020 and analyzes the temporal and spatial variation characteristics of green development in the Beijing-Tianjin-Hebei urban agglomeration, focusing on the temporal and spatial evolution characteristics. The specific conclusions are as follows:

(1) From the results of the entropy value method, in the green development evaluation index system of Beijing-Tianjin-Hebei, scientific and technological innovation, green "dual carbon", and economic growth have the greatest impact on the green development level, while green life has a relatively small impact on the green development level. We should actively play the driving role of scientific and technological innovation, green "dual carbon", and economic growth in the green development level.

(2) From the time perspective, the green development level of the Beijing-Tianjin-Hebei urban agglomeration generally shows a fluctuating upward trend. The average growth rate of the green development level of Beijing-Tianjin-Hebei cities from 2011 to 2015 was 6.75%, and from 2016 to 2020, it was 8.88%, an increase of 2.13 percentage points compared with 2011-2015.

(3) From the spatial perspective, the spatial evolution of the green development level of Beijing-Tianjin-Hebei cities from 2011 to 2020 is characterized by significant regional differences. The number of cities with high and higher green development levels in Beijing-Tianjin-Hebei has been increasing, and the overall green development level of Beijing-Tianjin-Hebei cities has shown

an obvious upward trend, but there are still regional differences in the green development level of Beijing-Tianjin-Hebei cities. The Beijing-Tianjin-Hebei urban agglomeration has gradually formed a spatial distribution pattern dominated by the agglomeration of "high green development level-high green development level, low green development level-low green development level".

5.2 Recommendations

Based on the above analysis, this paper believes that the green development level of the Beijing-Tianjin-Hebei urban agglomeration can be improved in the following three aspects:

(1) Grasp the development opportunities of the times and vigorously develop scientific and technological innovation under the goal of "double carbon" to improve the innovation capacity of green development. Economic growth is the intrinsic driving force of green development, and efforts should be made to develop a low-carbon and recycling economy to realize the goal of sustainable development. Further, improve green life and promote the comprehensive green development of Beijing-Tianjin-Hebei.

(2) Strengthen the government's environmental regulations and establish a sound long-term mechanism. Ecological responsibility should be taken into account in planning and long-term development. Long-term regional planning should be carried out to improve the green development level of each province and city.

(3) The green development of Beijing-Tianjin-Hebei cities as a whole, requires the joint efforts of the whole region. Therefore, the scientific construction of Beijing-Tianjin-Hebei city development ecological pattern, green development, and urban construction, industrial layout, industrial development, and other areas of deep integration. Let the Beijing-Tianjin-Hebei city green development level regional differences gradually narrow.

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