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Analysis of the Pollution and Carbon Reduction Effects of the Coordinated Development of the Beijing-Tianjin-Hebei Region

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Abstract

Ecological coordination is a key objectives of the Beijing-Tianjin-Hebei (BTH) coordinated development strategy. As the construction of a Beautiful China enters a critical stage of synergistic governance for pollution reduction and carbon mitigation, scientifically evaluating the environmental benefits of the BTH coordinated development holds significant theoretical and practical importance. Based on New Economic Geography, Collaborative Governance Theory, and Innovation-Driven Theory, this paper constructs an analytical framework for regional coordination driving ecological governance. Using the 2014 elevation of BTH coordinated development to a national strategy as a quasi-natural experiment and provincial panel data, this study employs the Synthetic Control Method to assess its pollution and carbon reduction effects. Furthermore, Grey Relational Analysis identifies the core mechanisms. Results show the policy yields significant, sustained, and robust pollution and carbon reduction effects, confirming its well-timed implementation. The mechanisms operate through five dimensions: spatial restructuring and resource optimization, industrial upgrading and low-carbon transition, technological innovation and green spillovers, regional environmental collaboration, and transportation-energy integration. This study provides empirical evidence and policy insights for deepening regional coordinated governance and advancing synergistic pollution and carbon mitigation.

JEL classification numbers: R11, Q53, Q58.
Keywords: Beijing-Tianjin-Hebei Coordination, Pollution and Carbon Reduction, Environmental Governance, Synthetic Control Method.

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1. Introduction

Against the backdrop of accelerating global climate governance, China has achieved historic accomplishments in ecological civilization and environmental protection. However, the construction of a Beautiful China and the realization of carbon peaking and carbon neutrality goals remain arduous tasks. The energy structure of the BTH region exhibits rigid characteristics of being "coal-heavy, industry-heavy, and road-transportation-heavy." The region's total carbon emissions account for over 10% of the national total. Coupled with unfavorable natural conditions such as a "dustpan-shaped" terrain and frequent calm weather, the intensity of air pollutant emissions in BTH reaches more than three times the national average. Compared to the Yangtze River Delta and the Pearl River Delta, the BTH region faces more prominent development imbalances, greater difficulty in coordinated governance, and bears more complex pressures from compound ecological and environmental issues. Building a pioneering demonstration zone for a Beautiful China in BTH is a crucial measure for the national initiative.

The report of the 20th National Congress of the Communist Party of China explicitly proposed to "synergistically promote carbon reduction, pollution reduction, green expansion, and growth." Over the past decade, to address environmental and climate challenges, the BTH coordinated policy system has been continuously deepened. In February 2014, the coordinated development of BTH was elevated to a major national development strategy. The core of BTH coordination lies in further optimizing the regional spatial pattern, focusing on breakthroughs in transportation coordination, ecological environmental protection coordination, and industrial coordination, thereby achieving complementary regional advantages and enhancing overall regional development efficiency.

In recent years, the atmospheric and water environments in BTH have significantly improved. PM2.5 concentrations in the three regions have dropped by about 60% compared to ten years ago. In 2024, the proportion of days with good air quality in the BTH region approached 75%, and all surface water sections classified as worse than Grade V were eliminated. However, research on the ecological and environmental effects of BTH coordination remains insufficient. Existing studies mostly focus on the economic benefits of regional coordination and have yet to form a holistic analytical framework connecting policy, mechanism, and effect. Therefore, under the guidance of the national strategic goal of synergistic pollution and carbon reduction, analyzing and evaluating the effects of BTH coordinated development is particularly necessary. It holds significant importance for further promoting policies related to the dual-carbon goals and can provide a basis for pathways of synergistic environmental and climate governance in the process of regional coordination.

2. Literature Review

2.1 Research on Regional Coordination Policy Evaluation

The core purpose of regional coordination policies is to optimize the overall regional development pattern through cross-regional resource allocation and collaborative mechanisms. Domestic and international research mostly focuses on evaluating the impact of regional coordination policies on the economy, ecological environment, and social development. For instance, Ren (2020) evaluated both the overall returns of regional policies and their heterogeneous impacts on different entities. Han (2019), through an evaluation of 14 urban agglomerations in China, found that regional coordination policies can significantly promote overall economic growth in urban agglomerations. You Jihong et al. (2019) and Deng Rongrong et al. (2021) explored and found that regional coordination and cooperation significantly drive emission reduction effects and improve eco-efficiency in urban agglomerations.

Regarding research methods, Abadie and Gardeazabal (2003) proposed the Synthetic Control Method (SCM) to evaluate policy effects. Its basic idea is to construct a "counterfactual" control unit based on existing data and the target unit, comparing the differences between the target unit and the control unit after policy implementation to assess the policy effect. Domestic scholars Liu Youjin (2018) used SCM to objectively evaluate the impact of property tax policies on industrial relocation. Wang Yu et al. (2020) employed the Propensity Score Matching-Difference-in-Differences (PSM-DID) method to study the impact of the BTH regional coordinated development policy on public service supply efficiency. Liu Binglian et al. (2024), from the perspective of policy synergy, combined natural language processing technology and text analysis methods to quantify BTH industrial coordination policies.

2.2 Research on Beijing-Tianjin-Hebei Coordination

Scholars have used the BTH regional coordinated development strategy as a quasi-natural experiment, applying SCM to analyze the policy implementation effects on resources, economy, services, management, and other indicators to identify policy effectiveness. For example, Zhao Jianqiang (2023) used SCM to evaluate and found that BTH coordinated development effectively enhanced the regional scientific and technological innovation level. Wang Jinying et al. (2020) assessed the economic growth effects of the BTH regional coordinated development policy on the urban agglomeration. An Shuwei et al. (2022) evaluated the positive effects of the BTH coordinated development policy on environmental improvement and transportation synergy. Wang Dianru et al. (2022), considering regional differences in policy effects, concluded through SCM that the BTH coordinated development policy did not significantly drive Hebei Province's economic growth but promoted its industrial structure optimization and air quality improvement. Liu Jiayao et al. (2024) comprehensively utilized coupling coordination degree and gravity-standard deviation ellipse to measure the spatiotemporal characteristics of the synergy between "pollution reduction, carbon reduction, and economic development" in the BTH urban agglomeration, and used the obstacle degree model to analyze key barrier factors affecting synergy improvement.

Overall, research on key areas such as economy, environment, and transportation in BTH coordinated development is increasingly abundant. However, at the policy evaluation level, existing studies pay more attention to local aspects of BTH coordination, and the research perspective leans towards economic effects. There is a scarcity of comprehensive evaluations integrating regional coordination strategies with pollution and carbon reduction into a unified framework.

2.3 Research on Regional Pollution and Carbon Reduction Effects

In measuring pollution and carbon reduction, Yang et al. (2019) used an improved entropy-weighted TOPSIS model to measure the environmental pollution index of various provinces to characterize local ecological environmental quality and pollution levels. Zhu Bangzhu et al. (2025) evaluated China's inter-provincial pollution and carbon reduction synergy from 2014 to 2021 and used geographically and temporally weighted LASSO regression models to identify key driving factors. Di Qianbin et al. (2022) used correlation coefficient matrix methods and composite system synergy models to measure the synergy of pollution and carbon reduction governance in urban agglomerations, revealing the spatiotemporal imbalance characteristics of China's pollution and carbon reduction effects. Regarding key mechanisms and influencing factors driving pollution and carbon reduction, Lu Min (2022) used the entropy-weighted TOPSIS model, DID model, and SCM to empirically test the effects of pollution and carbon reduction. He Qizhi (2025) found that technological innovation and industrial structure optimization positively contribute to synergy enhancement. Yu Shijun (2025) further proposed that R&D investment, industrial structure, per capita GDP, and urbanization rates are the main factors promoting synergy. Cui Lianbiao et al. (2023) found the key roles of energy intensity, urbanization rate, and industrial structure upgrading in BTH coordination. Yuan Weipeng et al. (2022) further proposed from the urban scale that natural and socio-economic factors such as precipitation and innovation-entrepreneurship levels jointly affect pollution and carbon reduction effects, highlighting the necessity of multi-dimensional coordinated governance.

It can be seen that regarding influencing factors, scholars have discussed multiple dimensions such as energy intensity, technological innovation, industrial structure, economic development, R&D investment, and natural conditions. However, existing research still lacks horizontal comparisons of the relative importance of key driving factors. In view of this, this paper first integrates regional coordination strategies with pollution and carbon reduction into a unified framework, quantifies the multi-pollutant synergistic governance effect through entropy weight and empowerment methods, uses SCM to quantitatively evaluate the environmental effects after the implementation of this strategy, and applies Grey Relational Analysis to compare the evolution trends of pollution and carbon reduction before and after coordination.

3. Theoretical Mechanism and Research Hypotheses

3.1 Theoretical Framework

The BTH coordinated development takes the relocation of non-capital functions as the core starting point. By breaking administrative barriers and market segmentation, it drives the collaborative reconstruction of five major systems: regional space, industry, technology, governance, and factors, thereby promoting pollution and carbon reduction. This paper integrates New Economic Geography, Collaborative Governance Theory, Endogenous Growth Theory, and Industrial Ecology Theory to construct an analytical framework: Regional Coordination → Five Core Mechanisms → Pollution and Carbon Reduction. It optimizes resource allocation efficiency through spatial restructuring, promotes low-carbon transformation through industrial upgrading, releases green spillover effects through technological innovation, internalizes externalities through regional ecological collaborative governance, and reduces the entire chain of emissions through transportation and energy integration, ultimately achieving regional pollution and carbon reduction efficiency gains.

3.2 Five Core Action Mechanisms

3.2.1 Spatial Restructuring and Resource Allocation Optimization Mechanism

Based on the Core-Periphery Model of New Economic Geography, BTH has long suffered from spatial imbalance characterized by "excessive agglomeration in Beijing and scattered factors in Hebei." Administrative barriers lead to low efficiency in the allocation of land, energy, and labor. Coordinated development reshapes the spatial pattern of population and industry by relocating non-capital functions and constructing the "Two Wings" (Xiong'an New Area and Beijing Municipal Administrative Center), breaking administrative division constraints. This includes: relocating general manufacturing and regional logistics bases, guiding factors to gather in node cities with higher environmental efficiency; coordinating infrastructure co-construction and sharing to reduce resource consumption and pollution emissions caused by redundant construction; realizing intensive land use and efficient factor allocation to reduce environmental loads from the source caused by extensive development.

3.2.2 Industrial Structure Upgrading and Low-Carbon Transition Mechanism

Based on Synergetics Self-Organization Theory, Structural Bonus Hypothesis, and Industrial Ecology Theory, regional coordination exerts the dual effects of government guidance and market self-organization evolution. Previously, BTH faced issues of industrial isomorphism, concentration of heavy chemical industries, and excess low-end production capacity, which were the core sources of pollution and carbon emissions. The regional coordination strategy first promotes the orderly transfer of industries through government guidance, effectively alleviating the dilemma of industrial isomorphism and low-end lock-in in BTH. With the deepening of the coordination strategy, the market drives industrial chains to extend towards high-end, service-oriented, and green directions, cultivating advanced manufacturing clusters and modern service industries, promoting the formation of green industrial chains, reducing the proportion of resource-dependent industries, and improving industrial added value and energy utilization efficiency, thereby achieving structural pollution and carbon reduction for the region as a whole.

3.2.3 Green Technological Innovation and Diffusion Mechanism

Based on Endogenous Economic Growth Theory, Porter Hypothesis, and Technology Spillover Effect, Beijing possesses top-tier national green R&D resources, while Tianjin and Hebei have industrial transformation capabilities and application scenarios. However, the innovation chains and industrial chains of the three places were long separated. Under the framework of coordinated development, by building a regional innovation community, the three places jointly carry out research on low-carbon and pollution control technologies. Utilizing technology spillovers reduces the marginal cost of emission reduction in surrounding areas, promotes the integration of the "innovation chain—industrial chain—supply chain," and enhances the overall green total factor productivity of the BTH region, thus forming a long-term mechanism for innovation-driven pollution and carbon reduction.

3.2.4 Regional Environmental Ecological Collaborative Governance Mechanism

Based on Collaborative Governance Theory, Transboundary Public Goods Theory, and Environmental Federalism, ecological environmental elements such as atmosphere and water have significant public goods attributes and transboundary mobility. Single administrative region governance is prone to "free-rider" behavior and externality failure. BTH coordinated development establishes governance mechanisms beyond administrative boundaries through measures such as regional ecological environmental joint prevention and control (e.g., establishing a regional air pollution prevention leadership group, unifying planning, standards, monitoring, and law enforcement, promoting joint air defense, watershed co-governance, and integrated ecological protection and restoration). This internalizes environmental externalities and uses binding indicators to force the three places to synchronously optimize their industrial, energy, and transportation structures, achieving region-wide collaborative pollution and carbon reduction.

3.2.5 Transportation and Energy Integration Mechanism for Carbon Reduction

Based on Environmental Externality Theory, Transaction Cost Theory, and Coase Theorem, high cross-border transportation costs and dependence on fossil energy are hard constraints for pollution and carbon reduction. Conversely, the positive externalities of green energy and clean transportation suffer from insufficient supply due to the lack of reasonable benefit compensation mechanisms. BTH reduces transportation emissions by building a "Railway-integrated Beijing-Tianjin-Hebei" and promoting the "road-to-rail" (Gongzhuan tie) multimodal transport model. The three places coordinate to promote the green and low-carbon transformation of energy, expand the use of renewable energy, reduce the proportion of coal consumption, and promote the integration of electricity, natural gas, and green power markets. Through infrastructure sharing and market-oriented mechanisms, the systemic costs of clean transformation are reduced, achieving low-carbon development in all fields.

3.3 Research Hypotheses

Based on the above mechanism analysis, this paper proposes the following two research hypotheses:

H1: The Beijing-Tianjin-Hebei coordinated development policy can produce significant and robust effects on pollution and carbon reduction.

H2: Spatial restructuring, industrial structure upgrading, green technological innovation, environmental governance synergy, and transportation and energy integration are the core driving mechanisms.

4. Research Design

To scientifically evaluate the effectiveness of the BTH coordinated development strategy in pollution and carbon reduction, this paper considers both pollution control and carbon emission reduction goals, constructing a Comprehensive Pollution and Carbon Reduction Index as the core measurement basis. On this basis, taking the elevation of the strategy to a national strategy in 2014 as the quasi-natural experiment node, the period from 2004 to 2013 is designated as the pre-policy window, and 2014–2023 as the post-policy window. The Synthetic Control Method (SCM) is adopted. By selecting predictive variables suitable for the coordination policy, the difference in the CPCRI between the actual BTH and the synthetic BTH is compared to test the net policy effect. Furthermore, given the characteristics of the small-sample panel data of BTH from 2004 to 2023, Grey Relational Analysis (GRA) is used to compare the evolution trends of pollution and carbon reduction before and after coordination.

4.1 Measurement of the Dependent Variable: CPCRI Score

Since pollutant emissions cover multiple environmental media such as the atmosphere, water bodies, and solid waste, this paper refers to the comprehensive evaluation index system constructed by Wang Han et al.(2022) based on energy economy and pollutant and carbon dioxide emission data, combined with the development stage of the BTH region. It selects pollutants covering the atmosphere, water bodies, and solid waste. Considering data availability, policy relevance, scientificity, and representativeness, and based on the perspective of environmental regulation and the needs of "zero-waste city" construction, three positive indicators related to environmental governance control and input are selected. Some variables were not included in the study due to incomplete data during the sample period (for example, nitrogen oxide emission data only became fully available from 2011, resulting in a limited sample size).

To solve the problem that large differences in the dimensions of positive indicators dilute the weight of key indicators and fail to meet practical needs, this paper processes the CPCRI indicators in two categories and combines weighting: Core Performance Indicators (Negative, directly characterizing environmental quality and carbon emission levels): Entropy-weighted TOPSIS model is used for weighting—based on the degree of data variation, it objectively reflects the discrimination ability of indicators, avoids subjective arbitrariness, handles dimensional differences, and makes weight distribution more consistent with actual data characteristics. Positive Support Indicators (Governance input and resource recycling): Due to large dimensional differences and theoretically equivalent importance, they are given equal weights, reflecting their equally fundamental role in collaborative governance.

The combined weighting ensures the objectivity of core indicators while balancing the policy equilibrium of supporting indicators, ultimately yielding the C_score. The selection and weights of each variable are shown in Table 1.

Table 1: Pollution and Carbon Reduction Indicators

Variable Name	Unit	Selection Rationale	Direction	Weight
PM2.5 Concentration	μg/m³	Core indicator of air pollution	Negative	25.8%
COD in Wastewater	10,000 tons	Key indicator of organic water pollution	Negative	29.2%
SO2 Emission Intensity	10,000 tons/100 million yuan	Symbolic indicator of air pollution	Negative	5.1%
CO2 Emission Intensity	10,000 tons/100 million yuan	Same root and origin as various air pollutants	Negative	9.9%
Comprehensive Utilization Rate of General Industrial Solid Waste	%	Reflects resource recycling level	Positive	10%
Industrial Pollution Control Investment per Unit GDP	%	Reveals the hard constraints and soft inputs implemented by regions to improve environmental quality	Positive	10%
Harmless Treatment Rate of Domestic Waste	%	Characterizes urban domestic pollution load	Positive	10%

4.2 Policy Effect Evaluation via Synthetic Control Method

4.2.1 Selection of Predictive Variables

Based on the mechanism of pollution and carbon reduction and the specificity of the BTH region, and referring to previous literature on BTH coordination mechanisms and core drivers of environmental impact and carbon emissions (Shang,2024), this paper selects key predictive variables from three dimensions (Li,2025): industry, transportation, and ecology, adhering to the principles of relevance, exogeneity, and stability:

a. Industrial Dimension — Industrial Structure Hierarchy Coefficient + Industrial Structure Optimization Index

The industrial structure hierarchy coefficient measures the degree of industrial climbing towards high added value and from labor-intensive to technology-intensive, capturing industrial structural differences in BTH during industrialization. The industrial structure optimization index is the output ratio of the tertiary industry to the secondary industry. The primary task of BTH coordination is industrial transfer and upgrading. Controlling this index before the policy ensures that the synthetic group is similar to BTH in terms of industrial advancement, stripping away the additional pollution and carbon reduction effects purely from policy coordination.

b. Transportation Dimension — Transportation Network Density

Measured by the ratio of highway and railway mileage to regional area, reflecting the level of regional transportation infrastructure and economic activity intensity, and directly related to mobile source emissions. Matching this indicator avoids underestimating the pre-policy emission levels of the synthetic group due to sparse transportation, ensuring the comparability of traffic loads.

c. Ecological Coordination Dimension — Energy Consumption Intensity & Energy Conservation and Environmental Protection Investment Ratio

Energy consumption intensity measures the regional economy's dependence on energy and energy utilization efficiency, a key driver of carbon emissions. Controlling this indicator ensures that the synthetic group is similar to BTH in technical efficiency and energy structure, separating the contribution of coordination policy to energy efficiency. The energy conservation and environmental protection investment ratio reflects local environmental willingness and fiscal support, controlling regional differences in environmental regulation, and avoiding misattributing the emission reduction effects brought by increased environmental investment to coordination policy.

4.2.2 Model Construction

a. Basic Setup

Sample Scope: 2004–2023 panel data of 30 Chinese provinces (Tibet excluded due to missing data).

Treatment Group: Beijing, Tianjin, Hebei (ID=1/2/3).

Policy intervention time point: 2014.

Control Group: Excluding Yangtze River Delta provinces, the remaining 23 provincial-level administrative regions without regional coordination policy are weighted to synthesize "BTH."

Dependent Variable: CPCRI (C_score).

Predictive Variables: C_score before 2014 (baseline environmental performance).

Covariates: Industrial structure hierarchy coefficient (industry1), industrial structure optimization index (industry2); transportation network density (traffic); energy consumption intensity (eco1), energy conservation investment ratio (eco2).

The core of this method is to use a linear combination of a set of predictive variables to assign reasonable weights to other regions to simulate the characteristics of the real BTH region before policy implementation.

b. Objective Function

Minimize the difference in predictive variables and covariates between the treatment group (BTH) and the synthetic control group during the pre-intervention period (2004–2013):

$$\min_{W} \parallel X_1 - X_0 W \parallel = \sqrt{(X_1 - X_0 W)' V (X_1 - X_0 W)} \tag{1}$$

Symbol Definition:

X_1 is the covariate matrix of the treatment group (BTH), dimension K×1, containing the means of predictive variables and covariates in the pre-policy period (2004–2013); X_0 is the covariate matrix of the control group, dimension K×J(J=23 control provinces); $W = (\omega_2, \omega_3, \ldots\ldots, \omega_J)'$ is the weight vector, satisfying $\sum_{j=2}^{J} \omega_j = 1$ and $\omega_j \geq 0$; V is a diagonal matrix reflecting the relative importance of each covariate.

c. Mathematical Formalization of the Model

Since the C_score of 1+J provinces can be observed over T years, after merging BTH into a new ID, ID=1 represents the experimental group BTH, and J represents other provinces in the control group. Only province 1 was affected by the BTH coordinated development policy in year T_0 while the remaining J provinces were not intervened. Where t∈[1,T], satisfying $1<T_0<T$. Define C_score_{it} as the score of province i in year t, $C\_score_{it}^{Y}$ as the score of province iin year tunder policy intervention, and $C\_score_{it}^{N}$ as the score without intervention. The policy intervention effect can be expressed as: $\alpha_{it} = C\_score_{it}^{Y} - C\_score_{it}^{N}$.

4.3 Analysis of Driving Factors of BTH Pollution and Carbon Reduction Based on Grey Relational Analysis

4.3.1 Selection of Driving Factors

All driving factors are collected around the main line of BTH coordination, incorporating exclusive variables characteristic of BTH to avoid piling up generalized indicators. Referring to the research of Tang Xiangbo et al. (2022) and Ma Weibo et al. (2022), core driving factors are selected from the five core action mechanisms:

Table 2: Selection of Driving Factor Indicators

Primary Dimension	Secondary Indicator	Unit
Spatial Layout & Factor Allocation Optimization	Population Density	Persons/km²
	Urbanization Rate	%
	Built-up Area	km²
	Share of Fixed Asset Investment in GDP	%
	Total Investment of Foreign-invested Enterprises	Million USD
Industrial Structure Upgrading	Industrial Structure Hierarchy Coefficient	%
	Industrial Structure Optimization Index	%
	Revenue Share of Resource-dependent Industries	%
	Energy Consumption per Unit GDP	Tons of standard coal/10,000 yuan
	Number of Industrial Enterprises above Designated Size per 10,000 People	Units
Green Tech Innovation & Diffusion	Proportion of R&D Expenditure in GDP	%
	Number of Invention Patents per 10,000 People	Items/10,000 people
	Number of Patent Applications by Industrial Enterprises above Designated Size	Pieces
	Cumulative Number of Registered High-tech Enterprises	Units
Environmental Governance Synergy	Total Investment in Urban Environmental Infrastructure Construction	100 million yuan
	Harmless Treatment Rate of Domestic Waste	%
	Green Coverage Rate of Built-up Areas	%
	Word Frequency of Joint Prevention and Control	Count
	Proportion of Investment in Energy Conservation and Environmental Protection	%
Green Transport & Energy Structure	Proportion of New Energy Power Generation	%
	Proportion of Coal Consumption	%
	Proportion of Natural Gas Consumption	%
	Per Capita Urban Road Area	m²
	Transportation Network Density	%

4.3.2 Grey Relational Analysis Method

Due to the limited sample size of some BTH data and the fact that distributions do not completely follow a normal distribution, traditional regression analysis has certain limitations. Grey Relational Analysis does not require large samples or typical probability distributions. It can judge the strength of the association between various driving factors and the CPCRI by comparing the geometric shape similarity of sequences. It is especially suitable for handling systematic problems with small samples, incomplete information, and multi-factor interaction. Therefore, this paper divides the research interval into pre-coordination and post-coordination periods, calculates the grey relational degree of each driving factor with the CPCRI respectively, and compares the changes in relational degree to identify the staged characteristics of key drivers.

4.4 Data Sources

PM2.5 data comes from the China High Resolution and Quality PM2.5 Dataset (2000-2023) released by the National Tibetan Plateau Data Center. Provincial carbon dioxide emission data comes from the EDGAR , maintained by the Joint Research Centre of the EU and the International Energy Agency. This carbon emission data includes all fossil fuel CO2 sources. The EDGAR database is consistent with the IPCC inventory methodology and has been cross-validated with official emission reports from multiple countries, indicating high authority. COD and SO2 emission data come from the China Energy Statistical Yearbook. Remaining data are sourced from the China Statistical Yearbook, China Science and Technology Statistical Yearbook, local city statistical yearbooks, the China Economic and Information Statistics Network, and the National Economic and Social Development Statistical Bulletins of the three regions. Word frequency data for joint prevention and control are sourced from government work report statistics.

5. Empirical Analysis

5.1 Results of BTH Pollution and Carbon Reduction Scores

By calculating the annual average CPCRI of BTH, the trend change chart is obtained (Figure 1). Overall, from 2004 to 2023, the CPCRI of the BTH region rose from 57.4 to 63.4, an overall increase of 10.45%. This reflects the continuous accumulation of environmental pressure during the early stage of economic growth in the region. In the later stage (after 2014), driven by the dual impetus of the regional coordinated development strategy and the national dual-carbon goals, the three regions promoted measures such as industrial relocation, transportation integration, and environmental joint defense and co-governance, achieving certain results in pollution and carbon reduction.

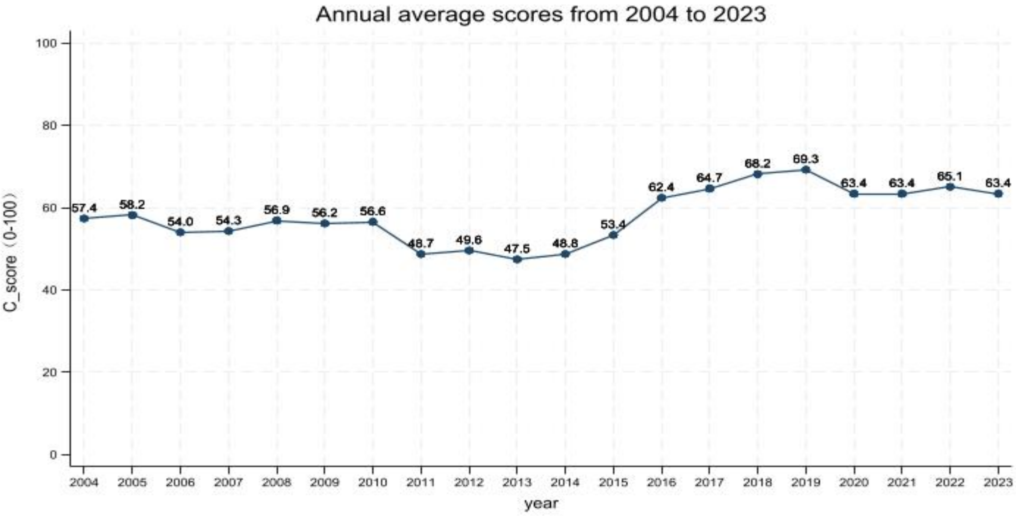

Figure 1: Trend of BTH Pollution and Carbon Reduction Scores

According to the trend of scores and policy background, 2004–2023 can be divided into four key stages, as shown in Table 3.

Table 3: Characteristics of BTH Pollution and Carbon Reduction Scores by Stage

Stage	Year and Score	Brief Description of Stage Characteristics
Fluctuation Platform Period	2004(57.4) →2010(56.6)	Rapid expansion of high-energy-consuming industries; energy consumption dominated by coal; environmental pressure intensified by heavy industrialization.
Significant Decline Period	2010(56.6) →2013(47.5)	Heavy industrial structure was the core feature of China's industrial structure changes during this stage. The "Four Trillion" investment plan stimulated high-energy-consuming industries, frequent heavy pollution incidents occurred, and scores declined significantly.
Synergy Improvement Period	2014(48.8) →2023(63.4)	Implementation of BTH coordinated development strategy and environmental governance synergy promoted economic transformation and ecological priority. Short-term fluctuations occurred due to the recovery of high-energy-consuming industries and increased transportation activity post-pandemic. Subsequently, with the optimization of industrial and energy structures, the dividends of the BTH coordinated N+1 pollution and carbon reduction policies will gradually be released.

5.2 Policy Effects via Synthetic Control Method

5.2.1 Synthetic Control Weight Distribution

Synthetic BTH =0.296*Jilin+ 0.098*Shandong+0.038*Hunan+0.122Guangdong+ 0.074*Guangxi +0.112*Chongqing +0.107*Guizhou +0.153*Ningxia

5.2.2 Fitting Effect and Robustness Test

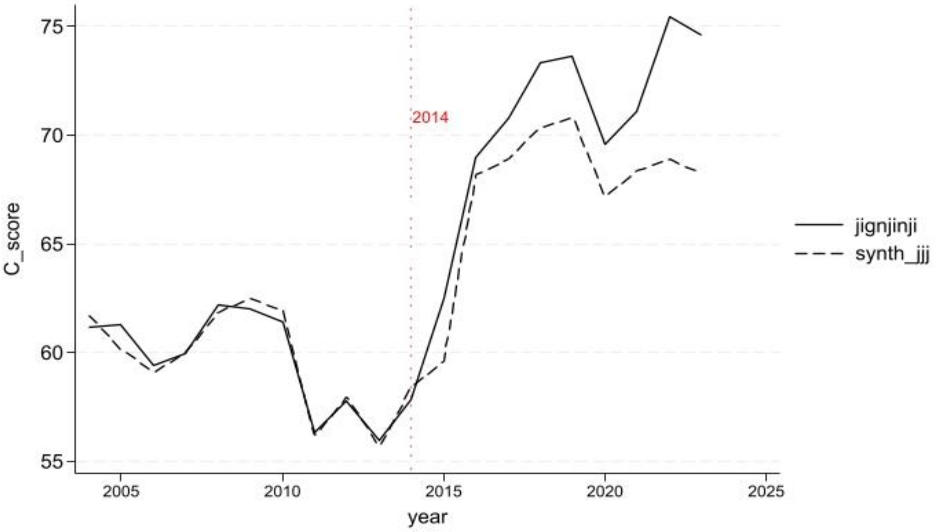

Figure 2: Synthetic Control Fit Chart

After standardizing the CPCRI data, Figure 2 illustrates the time paths of the BTH region and its synthetic control group in terms of pollution and carbon reduction effectiveness. During the pre-intervention period (2004–2014), the actual CPCRI of BTH closely matched the predicted values of its synthetic control group, indicating that the SCM successfully constructed a 'counterfactual' BTH region without the coordination policy. However, after 2014, the two paths gradually deviated significantly. The actual pollution and carbon reduction effect of the BTH region was significantly higher than that of its synthetic control group, and the positive gap steadily widened, indicating that the BTH coordination policy produced substantial pollution and carbon reduction effects.

Table 4: Differences in Predictive Variables

Predictive Variable	Treatment Group	Synthetic Control Group	Difference
Industrial Structure Hierarchy Coefficient	2.294787	2.293979	0.000808
Industrial Structure Optimization Index	1.027521	1.026366	0.001155
Transportation Network Density	0.6759354	0.6761562	-0.0002208
Energy Consumption Intensity	1.316011	1.316147	-0.000136
Energy Conservation Investment Ratio	0.0345236	0.0345186	0.000005

From the balance test in Table 4, the mean values of key predictive variables in the synthetic group are very close to those of BTH. Before the policy implementation, the Root Mean Square Prediction Error (RMSPE) between the synthetic BTH's CPCRI and the true value was 0.6513. Given that the average CPCRI during the sample period is 58.08, this error accounts for only 1.12% of the dependent variable mean and is far smaller than the treatment effect observed after the policy. This indicates that the synthetic control object captures the evolution path of the actual BTH well. Subsequent placebo tests also confirm that this imbalance does not affect the core conclusion that the policy is significantly effective and not driven by chance factors. Therefore, the current synthesis result possesses reliable counterfactual inference capability.

5.2.3 Placebo Test

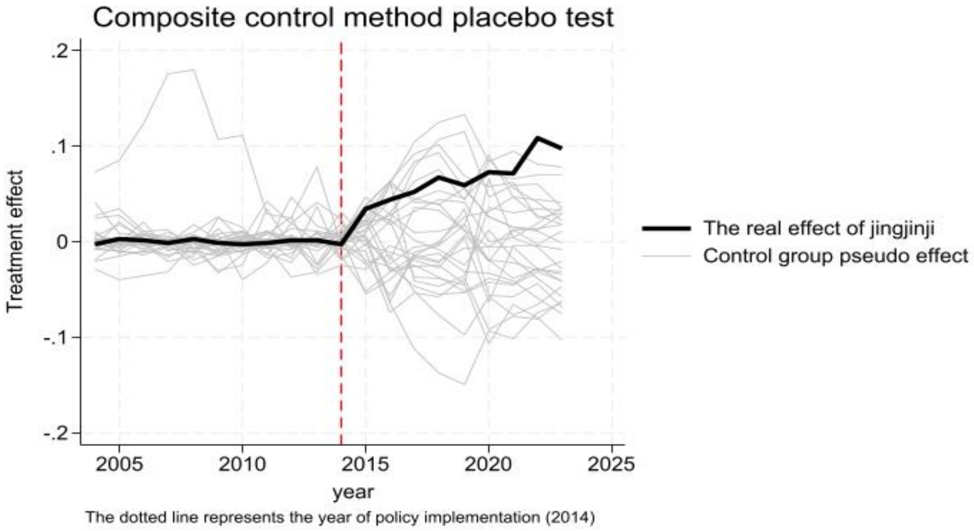

Figure 3: Placebo Test Chart

Figure 3 shows the results of the placebo test. Gray lines represent the pseudo-treatment effect trajectories of all potential control provinces, while the black bold line represents the true effect of BTH. The results show that before the policy implementation (2004–2014), except for one special province, the effect values of all provinces fluctuated randomly around zero, conforming to the parallel trend assumption. After the policy implementation (2014–2023), the BTH region exhibited a unique pattern distinct from the control group—its pollution and carbon reduction effect showed an overall upward trend, reaching a difference of 6.38 points by 2023.

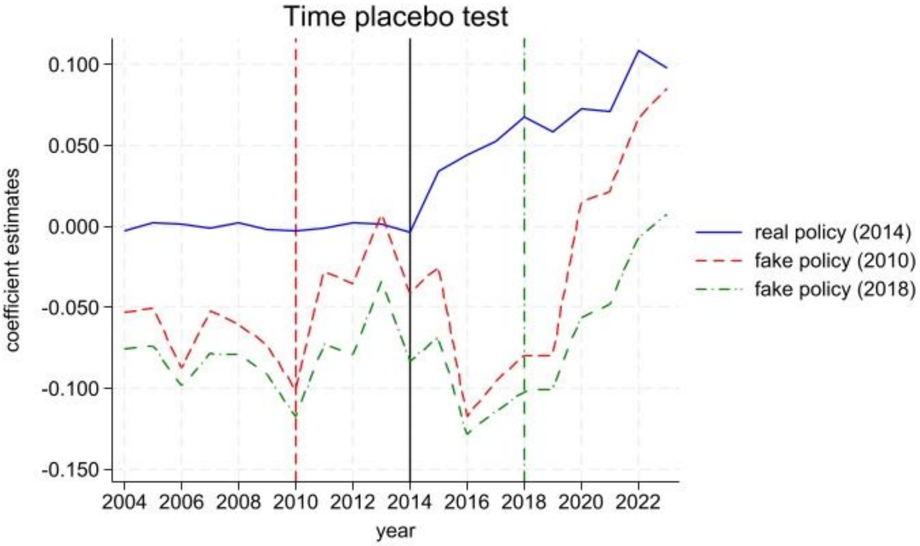

Figure 4: Time Placebo Test Chart

To exclude the doubt that "the policy effect stems from historical trend inertia or random fluctuations," this study virtually set the policy implementation years to 2010 and 2018, reconstructed the synthetic control groups, and measured the treatment effects. As shown in Figure 4, only at the actual policy point of 2014 did the difference between the synthetic group and the treatment group show a continuously expanding trend. Prematurely implementing coordinated pollution and carbon reduction policies easily leads to weak policy implementation due to insufficient supporting industrial transformation capabilities and a lack of fiscal support systems, making it difficult to form systematic pollution reduction and carbon sink enhancement pathways. Similarly, in 2018, although environmental protection technology had significantly progressed, the long-formed development model of high energy consumption and high growth led to strong institutional inertia among local governments and enterprises regarding green transformation. Policy intervention required higher coordination costs, which instead weakened policy effectiveness. Therefore, 2014 was a key year for the adaptation stage of the BTH coordinated development policy.

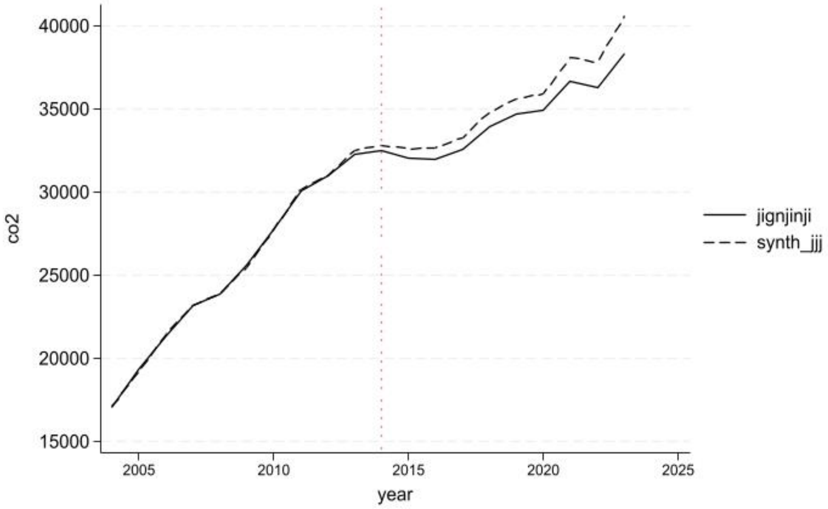

Figure 5: Replacement of Explained Variable

Considering that replacing the explained variable can further increase research robustness, Figure 5 presents the comparison results of BTH's CO2 emissions versus synthetic BTH emissions from 2004 to 2023, which is consistent with the core conclusion of this paper: after the implementation of the BTH coordinated development policy in 2014, real emissions continued to be lower than synthetic emissions, and the emission reduction effect strengthened over time.

Before the policy implementation, the real values highly matched the synthetic values, indicating that synthetic BTH could accurately replicate the emission trajectory of BTH before the policy, meeting the parallel trend assumption and laying the foundation for subsequent effect identification. In the policy launch year, actual BTH carbon dioxide emissions were 324.69 million tons, 3.31 million tons lower than the synthetic BTH's 328 million tons. From 2015 to 2023, emission reductions continued, and the difference gradually expanded. In 2023, actual carbon dioxide emissions were 383.38 million tons, 22.46 million tons lower than the synthetic BTH's 405.84 million tons, indicating that the BTH coordinated development strategy significantly reduced regional CO2 emissions.

5.3 Analysis of Driving Factors

The five core mechanisms proposed earlier will be analyzed for correlation in this section using Grey Relational Analysis.

5.3.1 Grey Relational Degree Results

Table 5: Grey Relational Analysis Results - Changes in Ranking

Primary Mechanism	Primary Dimension Ranking Change	Core Secondary Indicator Performance
Spatial Layout & Factor Allocation Optimization	3rd →1st 0.6944→0.8449	Population Density 7→3 Urbanization Rate 10→4 Total Foreign Investment 4→7
Industrial Structure Upgrading	4th → 2nd 0.6914→0.8402	Industrial Structure Hierarchy Coefficient 9→1 Resource-dependent Industry Revenue Share 5→15
Green Tech Innovation & Diffusion	2nd → 3rd 0.6987→0.8205	Invention Patents per 10,000 People 3→2 Industrial Enterprise Patent Applications 14→8
Environmental Governance Synergy	5th → 5th 0.6608→0.8021	Harmless Treatment Rate of Domestic Waste 16→9 Green Coverage Rate 17→12 Word Frequency of Joint Prevention & Control 13→22
Green Transport & Energy Structure	1st → 4th 0.7763→0.6842	New Energy Power Generation Share 1→14 Natural Gas Consumption Share 2→6 Transport Network Density 12→5

5.3.2 Analysis of Grey Relational Degree Results

As shown in Table 5, combining data from the two stages, the driving factors for BTH pollution and carbon reduction underwent significant transformations before and after the implementation of the coordination strategy. From the perspective of primary dimensions, from 2004 to 2013, the two strongest driving mechanisms were Green Transport & Energy Structure and Green Tech Innovation & Diffusion; while from 2014 to 2023, they adjusted to Spatial Layout & Factor Allocation Optimization and Industrial Structure Upgrading. In terms of correlation strength, the grey relational degrees of the five primary dimensions after coordination were higher than those before coordination, indicating that after the implementation of the Outline of the Beijing-Tianjin-Hebei Coordinated Development Plan, the effects of various driving factors on pollution and carbon reduction were enhanced overall, and regional synergy effects continued to emerge. However, the degree of enhancement among different mechanisms was inconsistent. Among them, structural factors such as spatial layout and industrial structure showed more obvious improvements, while the environmental governance synergy mechanism, though enhanced, remained relatively low overall, suggesting that the translation of environmental joint prevention and control effectiveness still has room for improvement.

Specifically:

1) Spatial Layout & Factor Allocation Optimization

The primary relational degree increased from 0.6944 to 0.8449, jumping to the first place, becoming the strongest driving mechanism for BTH pollution and carbon reduction after coordination. From secondary indicators, population density and urbanization rate rankings rose significantly. This indicates that the coordination strategy optimized the spatial distribution of population in BTH, generating economies of scale and factor integration effects. The role of population agglomeration, urbanization advancement, and cross-regional factor allocation optimization in pollution and carbon reduction was significantly enhanced. Although the correlation of foreign investment declined slightly, it remained high. The rankings of built-up area and fixed asset investment share were relatively low, indicating that the enhancement of the spatial layout mechanism mainly came from the improvement of population and factor allocation efficiency, rather than simply relying on urban scale expansion or investment-driven growth.

2) Industrial Structure Upgrading

The primary relational degree increased from 0.6914 to 0.8402, rising from 4th to 2nd place, indicating that industrial transformation and upgrading have become important pillars of pollution and carbon reduction under the background of regional coordinated development. From secondary indicators, the industrial structure hierarchy coefficient jumped from 9th to 1st place, becoming the single indicator with the highest correlation, indicating that the evolution of BTH industries towards high-end and high value-added directions is the core driver for improving regional pollution and carbon reduction quality and efficiency. Comparing the 2004–2023 long-cycle data (Table 6), the temporal evolution of the industrial structure hierarchy coefficient in BTH shows steady improvement, and the average value of this core indicator in the region is significantly better than the national average, highlighting the regional leading advantage and solid foundation of BTH industrial structure upgrading. The industrial structure optimization index remained at a medium level after coordination, further verifying the pollution and carbon reduction effect of industrial structure improvement. Meanwhile, the ranking of the revenue share of resource-dependent industries dropped significantly, while the number of industrial enterprises per 10,000 people rose slightly. This indicates that the regional economy's dependence on high-energy-consuming industries is being gradually broken, and the green transformation of industries is becoming a solid support for pollution and carbon reduction.

Table 6: Comparison of Industrial Upgrading between BTH and National Average

	Industrial Structure Hierarchy Coefficient		Industrial Structure Optimization Index	
Year	**(BTH)**	**(National)**	**(BTH)**	**(National)**
2004	2.4286	2.2656	1.3822	1.0094
2005	2.4483	2.2734	1.4575	0.9871
2006	2.4670	2.2874	1.5629	0.9734
2007	2.4733	2.2968	1.6556	0.9852
2008	2.4806	2.2994	1.7632	0.9892
2009	2.4969	2.3198	1.8342	1.0417
2010	2.5022	2.3193	1.8263	1.0126
2011	2.5153	2.3233	1.9088	1.0163
2012	2.5221	2.3337	1.9645	1.0543
2013	2.5312	2.3497	2.0476	1.1251
2014	2.5409	2.3629	2.1092	1.1721
2015	2.5655	2.3887	2.3281	1.3005
2016	2.5861	2.4098	2.4719	1.4043
2017	2.6026	2.4274	2.5793	1.4586
2018	2.6122	2.4429	2.6696	1.5174
2019	2.6237	2.4484	2.7955	1.5770
2020	2.6186	2.4426	2.7958	1.6191
2021	2.6049	2.4347	2.4938	1.5123
2022	2.6120	2.4311	2.7414	1.5291
2023	2.6264	2.4438	2.9482	1.5986

3) Green Technological Innovation & Diffusion

Although the ranking dropped slightly to 3rd place, the absolute value of the correlation degree increased significantly, indicating that technological innovation remains an important supporting mechanism for BTH pollution and carbon reduction. From secondary indicators, the number of invention patents per 10,000 people remained highly correlated in both stages, showing that innovation is the most stable power source for pollution and carbon reduction. The ranking of industrial enterprise patent applications rose by 5 places, reflecting that the coordination strategy effectively guided enterprises to transform green technology R&D into core competitiveness through policy incentives. The cumulative number of registered high-tech enterprises was at a medium level, while the R&D expenditure ratio ranking was relatively low, implying that although innovation input plays a role, future efforts need to focus more on the transformation of R&D investment into actual emission reduction achievements.

(4) Green Transport & Energy Structure Drive: The primary relational degree increased from 0.7763 to 0.8021, but the ranking dropped from 1st to 4th. This mechanism did not weaken; rather, it was surpassed by higher-level structural

factors such as spatial layout and industrial upgrading after coordination. From secondary indicators, the new energy power generation share and natural gas consumption share ranked 1st and 2nd respectively before coordination, reflecting the effect of early-stage energy transformation and air governance actions in BTH. After coordination, the ranking of transportation network density rose sharply by 7 places, confirming the contribution of the "Railway-integrated BTH" to improving transportation efficiency and directly reducing transportation carbon emissions.

(5) Environmental Governance Synergy Mechanism: The primary relational degree increased from 0.6608 to 0.6842, but ranked 5th in both stages, indicating that although this mechanism has improved, its overall driving effect remains relatively limited. From secondary indicators, the harmless treatment rate of domestic waste and green coverage rate rankings rose steadily, reflecting the effectiveness of refined urban governance, and the energy conservation investment ratio also increased. In contrast, the total investment in urban environmental infrastructure construction decreased in ranking, and the word frequency of joint prevention and control remained low. This suggests that environmental governance is more reflected in infrastructure improvement and governance level enhancement, but the synergistic effect of cross-regional environmental joint prevention and control mechanisms remains an important direction for advancing BTH pollution and carbon reduction effectiveness.

6. Conclusions and Implications

6.1 Conclusions

Through the Synthetic Control Method and multivariate empirical analysis, this paper evaluates the pollution and carbon reduction effects of the BTH coordinated development policy and discusses its main driving factors. The research conclusions are as follows:

1) The BTH coordination policy has significant and robust pollution and carbon reduction effects. The SCM results show that since the implementation of the coordination policy in 2014, the treatment group and the synthetic control group have shown significant and robust differentiation in the CPCRI, confirming that the coordination policy has a positive impact on regional pollution and carbon reduction. Placebo tests confirmed that the observed environmental improvement effects are indeed driven by the BTH coordination mechanism itself. Replacing the explained variable with CO2 emissions kept the conclusion robust, confirming that the BTH coordinated development strategy achieves significant carbon reduction effects while promoting economic growth.
2) The timing of policy implementation is reasonable and strategically forward-looking. The year 2014, as the policy shock point, precisely fits the deepening period of the national "Air Ten Measures" and the official launch period of the Outline of the Beijing-Tianjin-Hebei Coordinated Development Plan. It realizes the deep integration of top-level design and regional governance needs, and directly addresses the urgency of concentrated pollution control in the BTH

region, demonstrating a high degree of synergy between policy deployment and governance needs.

3) Pollution and carbon reduction show characteristics of multi-dimensional driving and convergent evolution. Grey relational analysis results show that the driving factors of BTH pollution and carbon reduction underwent a systematic reconstruction before and after the implementation of the coordination strategy in 2014. After the coordination policy, it mainly relied on spatial layout and factor allocation optimization and industrial structure upgrading to drive pollution and carbon reduction. Specifically, industrial advancement has become the primary driving force, and the intensive development of population and urbanization has generated obvious emission reduction dividends. The driving force of innovation no longer solely relies on government investment; enterprise-level patent applications and technology diffusion are becoming the core support of innovation. "Railway-integrated BTH" and promoting energy infrastructure interconnection are all key factors affecting regional carbon emissions. However, institutional synergy exhibits a lagging effect; the correlation ranking of the environmental governance synergy mechanism remains low, and the synergy advantage has not yet been fully transformed into governance effectiveness.

6.2 Implications

Based on the above research, BTH environmental governance has shifted from "extensive control" to "precise coordination." Its experience in pollution and carbon reduction has important demonstration value for implementing the "dual-carbon" goals. In response to the characteristics revealed by the empirical results—such as industrial advancement leading the way, spatial intensification highlighting, uneven innovation transformation, and persistent shortcomings in institutional coordination—the following suggestions are proposed to further deepen synergy effectiveness:

1) Focus on industrial advancement and spatial intensification to unleash structural synergy dividends.

Empirical results show that the industrial structure hierarchy coefficient has jumped to the forefront of driving forces, and the spatial layout dimension has the highest correlation. Focus on supporting high value-added, low-energy-consuming modern service industries and high-tech manufacturing industries to be rationally distributed within the region. Pay attention not only to industrial transfer but also to the overall upgrading of industrial levels and the advancement of industries towards high-end development. Utilize industrial level transitions to achieve structural emission reduction, completing the shift from simple industrial transfer to industrial capability leap. In view of the high correlation of population density, urbanization rate, and transportation network density, the synergy between the relocation of non-capital functions and the "Two Wings" construction (Xiong'an New Area and Beijing Sub-center) should be further strengthened. Using rail transit as a link, guide population and factors to gather along transportation corridors, reduce energy consumption and emission intensity per unit of output value through improved spatial allocation efficiency, and realize high-quality urbanization.

2) Use the construction of an innovation community as a lever to crack the bottleneck of R&D investment transformation.

Conforming to the rising trend of industrial enterprise patent applications, fiscal subsidies and financial support for green technology R&D cooperation among BTH enterprises should be increased. By expanding the application of carbon emission reduction support tools, guide high-tech enterprises to deeply participate in regional carbon neutrality technology research. Transform investment advantages into tangible emission reduction outputs. Addressing the disconnect between R&D expenditure and emission reduction effectiveness, a cross-regional green technology trading and transformation platform should be established to encourage the pilot testing and industrial landing of Beijing's high-level green scientific research achievements in Tianjin and Hebei.

3) Promote transportation and energy integration to break through the rigid constraints of the energy structure.

Amplify the emission reduction dividend of transportation network density: Accelerate the construction of the double-track Beijing-Xiong'an-Shangqiu and Xiong'an-Xinzhou high-speed railways, and promote the bus operation of intercity railways. Deepen multimodal transport such as the Tianjin Port-Xiong'an railway dedicated line, and use smart logistics scheduling systems to reduce the carbon footprint of the entire transportation process, transforming physical network connections into low-carbon transportation efficiency.

Crack the rigid constraint of coal consumption: Implement the target of continuously reducing total coal consumption through the dual approach of "energy-saving renovation of coal power + clean energy substitution." Strengthen the construction of cross-regional clean energy power transmission networks, utilize big data and artificial intelligence technology to monitor emissions of key enterprises in real-time, and build a multi-dimensional coupled energy internet system integrating electricity, industry, and transportation.

4) Strengthen the dual drive of environmental governance and market mechanisms to complement institutional coordination shortcomings.

In response to the empirical finding that the environmental governance synergy mechanism is persistently weak, it is necessary to push the governance model to transform from administrative commands to "institution + market." Summarize the experience of the "Air Ten Measures," establish a dynamic "Pollution and Carbon Reduction Index" monitoring system, and incorporate synergistic emission reduction effects into the rigid assessment indicators for the environmental inspection of the three local governments. Promote the regional co-construction of "zero-waste cities," shifting from end-of-pipe treatment to source reduction, linking facility investment with emission reduction volume for assessment. More importantly, regarding the robustness of carbon reduction identified in the empirical analysis, it is crucial to activate the vitality of the regional carbon trading market.

Relying on the Beijing Green Exchange, accelerate the construction of the BTH regional carbon trading sub-sector, and continuously break down administrative barriers. Stimulate the endogenous motivation and market vitality for the green transformation of traditional industries in Hebei and other regions through market-oriented means to reduce administrative control costs. Utilize cross-regional carbon trading and ecological compensation mechanisms to balance regional emission reduction costs and benefits, and enhance the substantive binding force of institutional coordination on pollution and carbon reduction.

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