Analysis of Carbon Emission Driving Factors and Study of Peak Paths under the Perspective of Spatio-Temporal Heterogeneity

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Abstract. Firstly, we compute the emissions of carbon in the Beijing, Tianjin, and Hebei of China, construct LMDI model, and decompose the CO2 drivers based on the perspective of spatio-temporal heterogeneity. Following the LMDI analysis results, three scenario models are suggested: a baseline scenario, a low-carbon model, and a high-carbon model. By integrating the current economic and social development status in Beijing-Tianjin-Hebei and relevant policies, specific model variables are defined to establish the STIRPAT model. Different carbon emission scenarios are then forecasted and evaluated using the STIRPAT model to determine the peak year and the maximum carbon emission level in the Beijing-Tianjin-Hebei region. The research indicates that (1) the highest carbon emission level will reach 377,712,600 tons in 2022 within the study period, with notable variations among different cities. (2) Economic development has the most significant impact on carbon emissions. (3) Under the low-carbon scenario, the 13 cities can attain the carbon emission peak target by 2030. These findings offer quantitative insights to support the transition towards low-carbon development in the Beijing-Tianjin-Hebei region.

1 Introductory

In response to the escalating global warming phenomenon, the issue of greenhouse gas and pollutant emissions has become a critical concern, threatening both ecological integrity and the sustainability of economic and social progress. In alignment with international efforts to combat the climate crisis, nations have been developing their own carbon neutrality goals tailored to their specific circumstances[1]. Being the largest emitter globally, China faces substantial pressure to decrease its carbon emissions[2-3].The Beijing-Tianjin-Hebei area, a major economic hub in northern China, is a key focus for energy consumption and air pollution control. The urgency to mitigate CO_2 emissions in this region is paramount. The spatial and temporal dynamics of carbon emissions in this urban cluster, along with the factors influencing them, can provide insights for developing strategies to support its sustainable development. Forecasting the timing of peak carbon emissions across the 13 cities of the Beijing-Tianjin-Hebei region under various scenarios is vital for China's ambition to "peak carbon emissions by 2030 and achieve carbon neutrality by 2060". The findings can also guide emission reduction efforts in other urban complexes, accelerating China's progress towards its carbon reduction targets and contributing to the global sustainability agenda. This research aims to enhance China's role in the worldwide pursuit of sustainable development.

2 Literature review

The study of carbon emission influencing factors is of great theoretical and practical significance for coping with climate change and improving related energy policies and low-carbon development strategies. Domestic and foreign related research results have been gradually enriched. Lv Jingye et al. (2022) [4] employed the LMDI model to analyze the factors influencing emissions in individual provinces across China, determining that energy intensity and R&D efficiency play a significant role as primary drivers.Zhiqi Wang et al. (2023) [5]applied the LMDI approach to dissect the elements influencing carbon emissions in the transportation sector of Western China, identifying the expansion of the economy as the principal factor driving the increase in carbon emissions. Lina Liu et al. (2024) [6]developed a system dynamics framework, revealing that coal usage is the primary contributor to carbon emissions. Overall, there is a wealth of research findings concerning the factors behind energy-related carbon emissions, encompassing a broad spectrum, making the LMDI model a more refined tool for analyzing the determinants of carbon emissions.

In addition, there are many scholars who have conducted a lot of research on the models for carbon emission prediction.Wang Libing et al. (2021) [7] established the STIRPAT model to predict China's energy carbon emissions in 2030. In summary, the existing studies on carbon emission prediction involves national, regional and provincial aspects, and the

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STIRPAT model can introduce multiple variables when assessing carbon emissions, and the prediction is more flexible and accurate when combined with the scenario analysis method.

After reviewing the existing literature, it is evident that previous researchers have extensively explored the factors influencing and predicting energy-related carbon emissions, yielding significant findings. The Beijing-Tianjin-Hebei region, a dynamic area in China characterized by robust economic growth and substantial energy consumption, presents spatial and temporal variations in carbon emissions, necessitating further investigation into the drivers and timing of peak emissions. This study employs the LMDI model to analyze the factors influencing energy carbon emissions in 13 cities within the Beijing-Tianjin-Hebei region and integrates the STIRPAT model with scenario analysis to forecast the carbon peak in the region. The research aims to contribute to carbon emission reduction efforts in the Beijing-Tianjin-Hebei region and support the coordinated and sustainable development of Chinese urban clusters.

3 Materials and Methods

3.1 Study area

The Beijing-Tianjin-Hebei area, spanning from 36.05° to 42.40° N latitude and from 113.27° to 119.50° E longitude, encompasses two centrally administered municipalities, Beijing and Tianjin, along with eleven cities at the prefectural level in Hebei Province as shown in **Fig.1.**Diagram illustrating the research domain: Beijing-Tianjin-Hebei. As a pivotal economic and political hub in China, the region boasts a sophisticated industrial network and significant growth momentum. Nonetheless, the Beijing-Tianjin-Hebei region faces challenges such as an inefficient energy mix, high energy usage, and significant carbon emission pressures, which hinder the cohesive and high-quality progression of the regional integration.

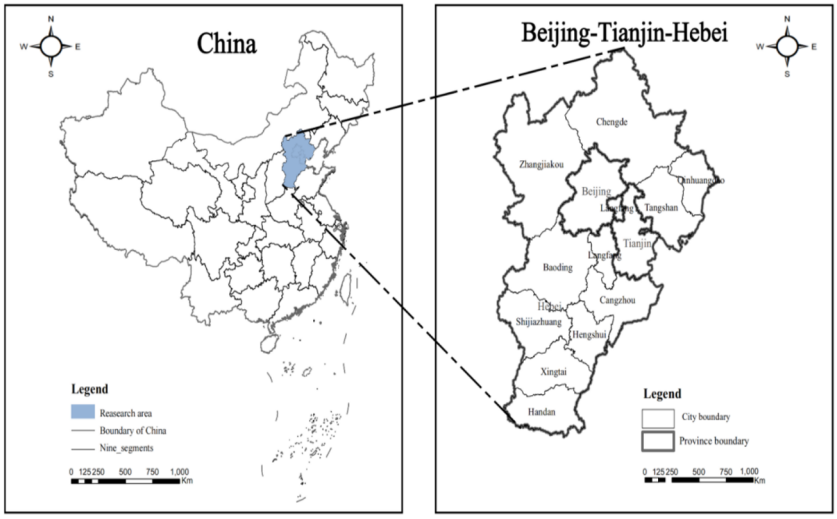


Fig.1. Diagram illustrating the research domain: Beijing-Tianjin-Hebei

3.2 Research methodology

3.2.1 Calculating the comprehensive carbon emission resulting from energy consumption

Utilizing the IPCC's guidelines and relevant carbon emission factors[8], the direct carbon emissions across the 13 cities in the Beijing-Tianjin-Hebei region are quantified. The formula for this quantification is expressed as follows:

$$C = \sum E_i (NCV_i \times EC_i \times COB_i \times \frac{44}{12}) \qquad (1)$$

where C denotes total CO_2 emissions, i denotes energy type; Ei denotes consumption of energy i; NCV is net calorific value of fuel; EC is carbon content, COB denotes combustion oxidation rate; 44/22 is molecular weight ratio of CO_2 to carbon.

3.2.2 LMDI Driver Decomposition Method

At the IPCC workshop in 1989, Kaya proposed the kaya constant equation. Based on this equation, the LMDI model constructed by Ang (2004) [9]was synthesized to decompose the carbon emissions of the 13 cities in the Beijing-Tianjin-Hebei region into the following four indicators: the economic development effect, the population scale effect, the energy structure effect, and the energy intensity effect.

$$\begin{aligned} I &= \sum_i \sum_j \frac{I_{ij}}{E_{ij}} \times \frac{E_{ij}}{E_i} \times \frac{E_i}{G_i} \times \frac{G}{P} \times P \\ &= \sum_i \sum_j CE \times ES \times EI \times A \times P \end{aligned} \qquad (2)$$

Where: I denotes the carbon output from fossil energy sources; E_i represents the energy usage in sector i; G_i stands for the gross domestic product; P indicates the year-end population. CE, ES, EI, and GP are the carbon

emission coefficient, energy mix, energy efficiency, economic expansion, and demographic factors, respectively. The equation to assess the influence of each factor is articulated as follows:

$$\Delta I_x = \sum_i \sum_j L(I_{ij}^t, I_{ij}^0) \ln(\frac{x^t}{x^0}) \quad (3)$$

Where: x represents the specific factor under consideration; ΔI_x signifies the impact of factor x on carbon emissions; $L(I_{ij}^t, I_{ij}^0)$ denotes the weighting factor; xt and x0 denote the values of the influencing factor in the target year and the reference year, respectively.

3.2.3 STIRPAT model

While the LMDI model is effective in analyzing the impacts of factors, it lacks the ability to forecast carbon emissions. To address this limitation and provide a dynamic analysis and prediction of carbon emissions in the Beijing-Tianjin-Hebei region, the STIRPAT model, an enhanced version of the IPAT equation developed by YORK et al., is introduced. The STIRPAT model, widely acknowledged for its effectiveness in studying carbon emission peaks, calculates parameters using logarithmic transformation and regression analysis, enabling the prediction of carbon emissions based on different scenarios. By utilizing scenario settings, the STIRPAT model follows a "top-down" approach and offers greater flexibility compared to other models in assessing the influence of various factors on environmental pressures. The fundamental structure of the model is as follows:

$$I = aP^b A^c T^d e \quad (4)$$

In the equation, where I, P, A, T represent environmental pressure, population size, affluence, and technology level, respectively; a is the model coefficient; b, c, d are the elasticity coefficients of the variables, respectively; e is the model error term. Beijing-Tianjin-Hebei is primarily driven by the secondary industry, and the expansion of this sector is expected to lead to increased carbon emissions. Therefore, the model incorporates the industrial structure (IS) as a new variable.

There are large differences in energy consumption between rural and urban Beijing-Tianjin-Hebei in the process of urbanization and development, so the urbanization rate (U) is included in the model.

In this study, carbon dioxide emissions are chosen to represent environmental pressure, GDP per capita represents the affluence term, and technology level considers industrial structure, energy intensity, and energy structure. Therefore, the study selects these six factors as independent variables to extend the STIRPAT model, and the extended model is shown in equation (5).

$$\begin{aligned} Ln(I) &= Ln(a) + bLn(P) + cLn(A) + dLn(U) \\ &+ fLn(IS) + gLn(EI) + hLn(ES) + Lne \end{aligned} \quad (5)$$

In the given model, "I" denotes the level of carbon dioxide emissions, "P" signifies the population factor, "a" stands for the average GDP per person, "U" is the indicator for the level of urbanization, "IS" characterizes the composition of the industrial sector, "EI" refers to the measure of energy intensity, "ES" represents the mix of energy sources. The parameter 'a' serves as the model's coefficient, while "b", "c", "d", "f", "g", and "h" are the elasticity coefficients for their respective variables, and "e" accounts for the model's error term.

3.2.4 Scenario setting

In setting the scenarios, the economic development level and social and livelihood situation of Beijing-Tianjin-Hebei over the years were taken into account, and the relevant variables were set to three modes, namely, low-carbon, baseline and high-carbon. The low carbon mode means that the rate of change of each variable slows down, and the benchmark mode assumes that each variable develops at a moderate rate, i.e., the rate of change of each variable is fast. According to the actual development situation of each city, the low-carbon mode is set to slow down by 0.2% to 1% compared with the baseline mode, and the high-carbon mode is set to be 0.2% to 1% faster than the baseline mode.

(1)Size of population

The Beijing Urban Master Plan (2016-2035) proposes that the resident population of Beijing should remain below 23 million from 2021-2025. It is assumed that the annual growth rate of Beijing's population under the baseline scenario is 0.65% from 2022 to 2030, reaching a peak of 23 million in 2023, and that the population growth rate from 2031 to 2040 is set at -0.1%; in the 14th Five-Year Plan of Tianjin, it is pointed out that the resident population of Tianjin will reach 15 million in 2025, so it is assumed that the population growth rate from 2022 to 2035 under the baseline scenario is set at 0.65%. In the "14th Five-Year Plan" of Tianjin, it is stated that the resident population of Tianjin will reach 15 million by 2025, so it is assumed that the average population growth rate of Tianjin in the baseline scenario will be 2% in 2022-2030, and the population growth rate will be set at -0.1% in 2031-2050. The government of Hebei Province clearly proposes that the total population will reach 79.1 million by 2035, so it is assumed that the average annual population growth rate of Hebei Province is 1% from 2022-2030 and -0.5% from 2031-2050 under the baseline scenario.

(2)GDP per capita

The relevant policy indicates that Beijing's GDP per capita reaches 210,000 yuan by 2025 and 320,000 yuan by 2035. The baseline scenario assumes that Beijing's GDP per capita grows at an annual rate of 5% from 2022-2030 and 3.6% from 2031-2050; Tianjin's GDP per capita grows at a rate of 6% up to 2035 and 4.5% from 2036-2050; and Hebei's GDP per capita grows at a rate of 6.6% from 2022-2025 and 2026- 5 percent in 2040.

industrial structure

From the Beijing-Tianjin-Hebei government report, it is known that the proportion of the secondary industry in

Beijing will be reduced, with an average annual rate of 2.8% in 2022-2025, followed by an average annual rate slowdown of 0.05% in 2026-2050; in Tianjin, the average annual rate will be 2% in the period of 2022-2025, followed by an annual rate slowdown of 0.1%; and in Hebei, the secondary industry will be reduced by an average annual rate of 0.6% in the period of 2022-2025, followed by a slowing down by 0.1% per year.

(3)Urbanization rate

As the Beijing-Tianjin-Hebei region undergoes further development, the pace of urbanization is expected to correlate with GDP fluctuations. In the baseline scenario, it is projected that the urbanization rate in Beijing will increase by an annual average of 0.1%, while in Tianjin, the annual increment will be 0.05% lower, and in Hebei, the rate will rise by an average of 1.2% annually.

(4)Energy intensity

With the introduction of the dual-carbon target, Beijing-Tianjin-Hebei has begun to focus on improving energy technologies and reducing energy consumption. The baseline scenario assumes that energy consumption per unit of GDP in Beijing-Tianjin-Hebei is reduced by 3% per year.

(5)Energy structure

In the context of the Beijing-Tianjin-Hebei regional energy planning, it is anticipated that under the standard scenario, there will be a reduction of 2% in the proportion of the energy mix within the region.

3.3 Data sources

Economic and social data, including GDP and population figures, are sourced from the statistical publications such as the Beijing Statistical Yearbook, Tianjin Statistical Yearbook, Hebei Statistical Yearbook, and the statistical bulletins of 11 prefecture-level cities in Hebei Province. Energy consumption data and other relevant information are obtained from the Energy Statistics Yearbook of each city within the Beijing-Tianjin-Hebei region. Conversion factors for different types of energy are derived from the China Energy Statistics Yearbook. In order to adjust for inflation effects, GDP figures are recalculated based on the 2005 constant prices.

4 Analysis of findings

4.1 Differences in carbon emissions across different locations and time periods

4.1.1 Temporal changes in Beijing-Tianjin-Hebei carbon emissions

According to Equation(1), the calculation of carbon emissions for the Beijing-Tianjin-Hebei urban agglomeration was conducted for the time span ranging from 2005 to 2022. As clearly illustrated in the graphical representation provided in Fig**Fig.2.**2006-2022 Beijing-Tianjin-Hebei carbon emissions, the trajectory of total carbon emissions within this particular urban agglomeration over the aforementioned period initially experienced an upward trend, followed by a downturn, and ultimately resumed an ascending pattern, culminating in the highest point observed throughout the entire study duration in the year 2022. The total quantity witnessed a substantial leap from a starting point of 208,253,200 tons to a final count of 377,712,600 tons, translating into a significant surge of 81.37%. The analysis can be further segmented into two distinct time frames: the initial phase spanning from 2006 to 2017 and the subsequent phase covering the years 2018 to 2022. During the former period, the Beijing-Tianjin-Hebei region underwent a phase of accelerated economic progression, which, in turn, led to the accumulation of regional wealth, accompanied by a parallel increase in energy consumption and, consequently, an upward tick in carbon emissions. The latter phase, however, was characterized by a relatively unchanged scenario in terms of carbon emissions within the Beijing-Tianjin-Hebei area, a situation primarily attributed to the influence of national-level policies implemented by China, which mandated Beijing to prioritize the enhancement of ecological preservation efforts and to systematically restructure its industrial sectors. Moreover, as the integration process of the Beijing-Tianjin-Hebei region has progressively advanced, the intercity synergistic effects have become increasingly pronounced, effectively curbing the previous growth trajectory of carbon emissions in the region. It is also pertinent to note that, in addition to these factors, the unforeseen impact of the novel coronavirus pandemic has served to dampen industrial production and societal activities across various regions within China, which has, in turn, contributed to a deceleration in the pace of carbon emissions growth.

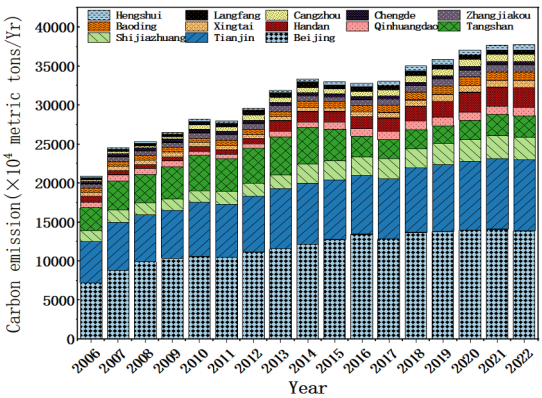


Fig.2.2006-2022 Beijing-Tianjin-Hebei carbon emissions

As shown in Fig.3, the urban centers within the Beijing-Tianjin-Hebei cluster exhibit varying degrees of contribution to the overall carbon emissions. Predominantly, the city of Beijing has been the largest emitter, accounting for a cumulative total of 2010,742,300 tons of carbon emissions over the 17-year period. In close succession, the cities of Tianjin, Tangshan, Shijiazhuang, and Handan have contributed significantly with respective emissions of 1265,414,600 tons, 591,224,700 tons, 361,586,300 tons, and 228,519,900 tons. The remaining prefecture-level cities

in the region have emitted less than 20,000,000 tons collectively during the same timeframe. Consequently, it is evident that curbing emissions in Beijing, Tianjin, and Tangshan will be pivotal in achieving carbon reduction targets for the entire Beijing-Tianjin-Hebei area.

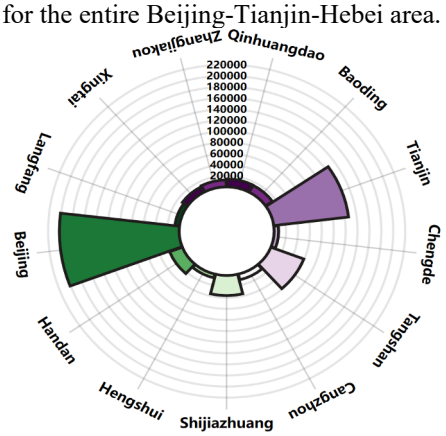
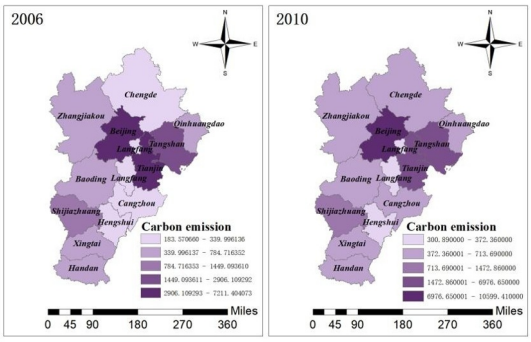


Fig.3. Beijing-Tianjin-Hebei carbon emissions from a spatial perspective

4.1.2 Spatial Changes in Carbon Emissions in the Beijing-Tianjin-Hebei Urban Agglomeration

As shown in Fig.**4**, the study utilized the year 2006 as a baseline and subsequent four-year intervals to analyze the spatial distribution of carbon emissions within the Beijing-Tianjin-Hebei region, with the assistance of Arcgis 10.8 software. The analysis revealed a consistent pattern over time, with higher emissions at the core and lower emissions in the periphery. Specifically, Beijing, Tianjin, and Tangshan consistently exhibited elevated levels of carbon emissions, in contrast with the surrounding urban areas that had comparatively lower levels. These three cities, being in close proximity, demonstrated a strong positive spatial correlation. As a traditional industrial hub in China, Tangshan's focus on heavy industries like steel and coal has contributed to its substantial energy consumption and carbon output due to its energy-intensive production methods. Meanwhile, cities like Hengshui, Cangzhou, and Xingtai, with less industrial development, consumed less energy, resulting in lower carbon emissions.



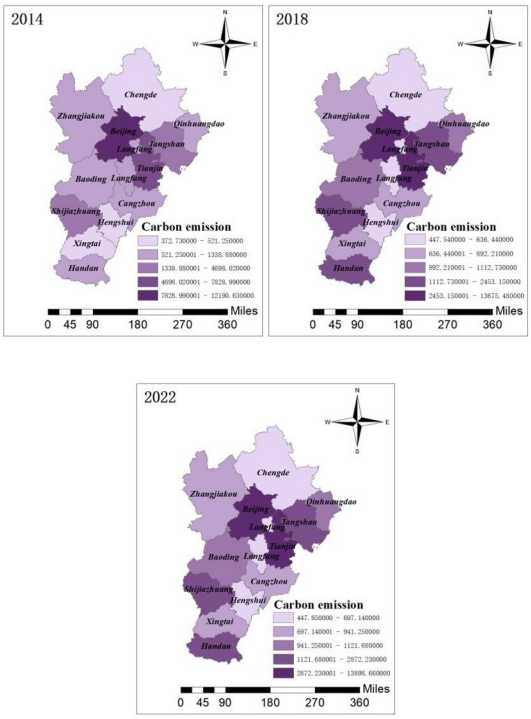


Fig.4. Beijing-Tianjin-Hebei carbon emissions from a spatial perspective(2006,2010,2014,2018,2022)

4.2 An Examination of the Determinants Affecting Carbon Emission Levels in the Beijing-Tianjin-Hebei Area

4.2.1 Time dimension

Integrating the spatial and temporal aspects of carbon emissions data for the Beijing-Tianjin-Hebei region, the LMDI method was utilized to annually dissect the underlying factors contributing to carbon emissions. With 2006 serving as the reference year, the method quantified the degree of influence for each of these contributing factors over time.As shown in Fig.**5**, from 2006 to 2022, carbon emissions have increased by an average of 10.59 million tons per year. The factors driving this increase include economic development and population growth, while the energy structure acts as a limiting factor. Additionally, the energy intensity factor alternately enhances or reduces carbon emissions over different years. The contributions of the drivers, listed in decreasing order of significance, are economic development, energy intensity, energy structure, and population size.

Overall, the impact of economic growth on carbon emissions is consistently positive, suggesting that economic development plays a role in increasing carbon emissions. The process of economic advancement requires substantial energy usage, and this surge in energy consumption inevitably results in a significant rise in carbon emissions.

Over the observed timeframe, the influence of energy intensity on carbon emissions was found to be positive in seven instances and negative in nine, suggesting

variability in its effect. Consequently, the Beijing-Tianjin-Hebei area should prioritize energy-intensive sectors in its strategies for energy saving and carbon emission reduction, aiming to use energy intensity as a means to curb the increase in carbon emissions.

In terms of the impact from the the energy structure effect, only in 2007 did it contribute to an increase in carbon emissions, while in all other years, it exerted a suppressive influence. Hence, the Beijing-Tianjin-Hebei region should capitalize on the mitigating role of the energy mix effect, persist in refining the energy composition, decrease the reliance on coal in the energy mix, and actively advance initiatives to reduce coal consumption and carbon output.

Compared with the first three drivers, the population size effect does not contribute much to the promotion of carbon emissions. China's aging trend is becoming more and more obvious, the birth rate is declining, and there may even be negative population growth in the future. Even though the positive contribution of population to carbon emissions is not obvious, the region should publicize the "dual-carbon" goals and policies, and guide residents to conserve resources and protect the environment in their daily lives.

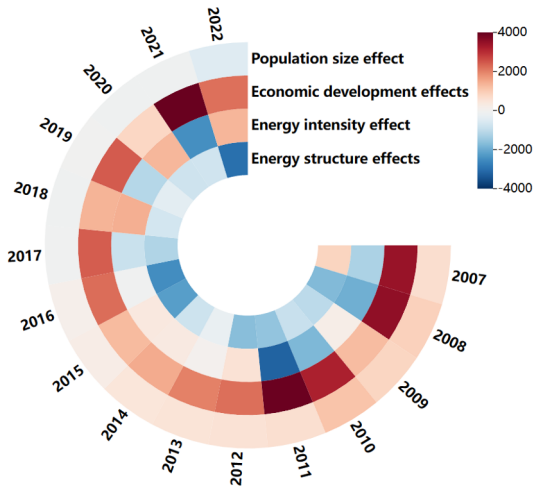


Fig.5. Heat map of decomposition of Beijing-Tianjin-Hebei carbon emission drivers

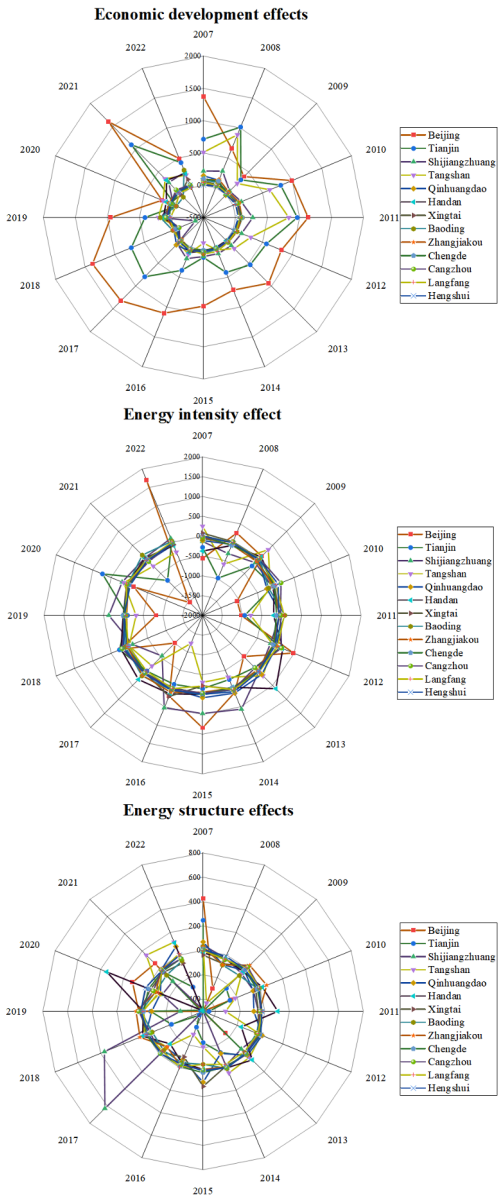
4.2.2 Spatial dimensions

From the spatial dimension, the contribution values of the four drivers of carbon emissions from 2006 to 2022 are shown in the figure. As can be seen in Fig.6, there are considerable disparities in the contribution values of the drivers across the 13 cities in the Beijing-Tianjin-Hebei region.

In the Beijing-Tianjin-Hebei region, the level of economic development significantly influences carbon emissions, with Beijing, Tianjin, and Tangshan leading in GDP and carbon emissions due to their advanced economic development. Conversely, cities like Zhangjiakou, Hengshui, Chengde, and Xingtai have lower economic development and subsequently lower carbon emissions. Therefore, improving the economic development model in each city is crucial for reducing carbon emissions effectively. Additionally, enhancing energy efficiency, as demonstrated by Beijing, Tianjin, and Tangshan through low-carbon city initiatives and energy efficiency policies, is essential. Other cities in Hebei Province, including Shijiazhuang, can benefit from sharing and adopting similar energy policies to improve energy efficiency.

In terms of the impact of energy structure, Handan stands out from other cities as having a significantly higher positive contribution to carbon emissions. Therefore, Handan needs to reduce its reliance on coal and focus on developing new energy sources. The other cities show less variation in the contribution of energy structure to carbon emissions.

The population size effect has a relatively minor influence compared to other factors. Only during the years 2007-2016 was the population size effect significant in Beijing and Tianjin. More recently, the contribution of population size to overall trends in these cities and throughout the region has been low.



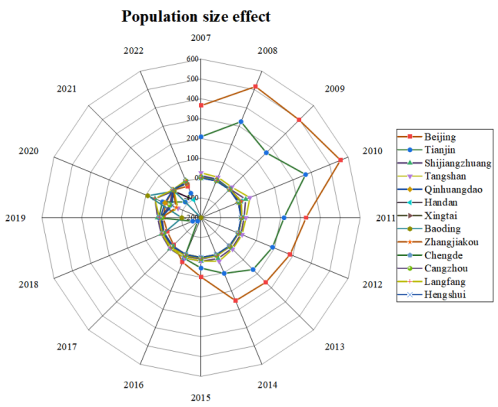


Fig.6. Impact of drivers on carbon emissions from a spatial perspective

4.3 Carbon emission projections based on the STIRPAT model

4.3.1 Ridge regression results

To solve the problem of multicollinearity among variables, ridge regression was chosen to analyze in this paper. Ridge regression abandons the unbiasedness of the least squares method, and makes the regression coefficients more practical and reliable at the cost of reduced precision, which is stronger than the fitting of the least squares method to pathological data. Ridge regression using SPSS 26 was performed separately for 13 municipalities. The smaller the ridge parameter K is, the less information is lost. So this paper takes K=0.1. ridge regression equations are shown in Table **1**. The R2 of all the equations are between 0.9-0.99, which proves the goodness of fit and Sig. < 0.05, which satisfies the statistical significance.

Table 1. Ridge regression equations

City	Ridge regression equation
Beijing	LnI=4.926+0.535LnP+0.105LnA+2.65LnU-0.354LnIS+0.01LnEI-0.053LnES
Tianjin	LnI=8.162+0.136LnP+0.156LnA+1.37LnU-0.09LnIS+0.065LnEI-0.117LnES
Shijiazhuang	LnI=2.658+1.53LnP+0.244LnA+0.172LnU-0.152LnIS+0.27LnEI-0.006LnES
Tangshan	LnI=1.102+1.429LnP+0.383LnA+0.007LnU+0.698LnIS+0.59LnEI-0.415LnES
Qinhuangdao	LnI=3.205+1.916LnP+0.146LnA+0.393LnU-0.112LnIS+0.635LnEI+0.14LnES
Baoding	LnI=6.342+0.193LnP+0.229LnA+0.065LnU-0.188LnIS+0.091LnEI-0.154LnES
Cangzhou	LnI=-11.395+3.071LnP+0.478LnA-0.05LnU+0.023LnIS+0.085LnEI+0.155LnES
Chengde	LnI=2.937+0.653LnP+0.201LnA-0.012LnU-0.023LnIS+0.282LnEI-0.068LnES
Handan	LnI=4.926+0.535LnP+0.105LnA+2.65LnU-0.354LnIS+0.01LnEI-0.053LnES
Hengshui	LnI=4.537+0.637LnP+0.339LnA+0.126LnU-0.42LnIS+0.651LnEI-0.59LnES
Langfang	LnI=10.382+0.201LnP+0.555LnA+0.107LnU+0.024LnIS+1.205LnEI0.038LnES
Xingtai	LnI=5.669+0.302LnP+0.178LnA+0.107LnU-0.707LnIS+0.619LnEI-0.088LnES
Zhangjiakou	LnI=2.201+0.714LnP+0.215LnA+0.256LnU-0.343LnIS+0.196LnEI0.08LnES

4.3.2 Prediction model error tests

Before conducting forecasting research, it is crucial to confirm the validity of the model by testing the model error. The per capita GDP, secondary industry ratio, population size, energy intensity, urbanization rate, and energy structure of the 13 cities in Beijing-Tianjin-Hebei were inputted into their corresponding ridge regression equations from 2006 to 2022. The calculated model predicted values of carbon emissions were then compared with the actual emissions to assess the accuracy of the model, as shown in Fig.**7**. The results show that the average error of the respective ridge regression models of the 13 cities is within 3%, and the predicted values of the carbon emission models basically coincide with the actual carbon emissions, indicating that the above equations can be applied to predict the future carbon emissions of the 13 cities in the Beijing-Tianjin-Hebei region.

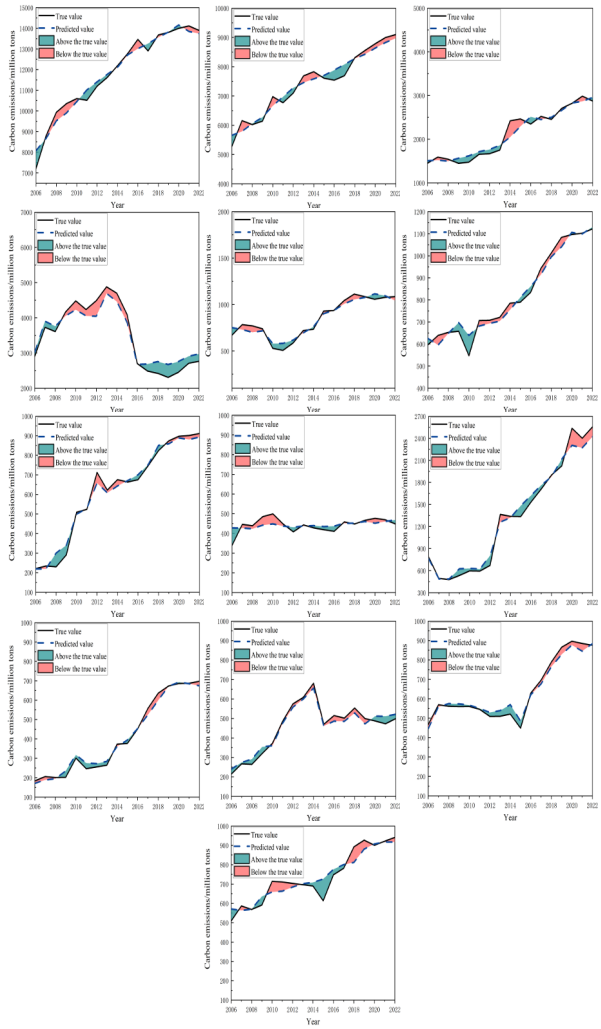
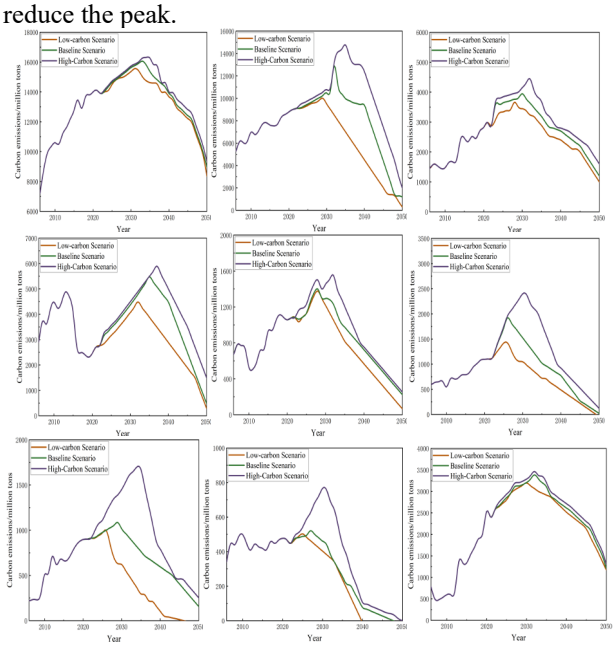


Fig.7. Results of forecast errors in 13 cities(Beijing,Tianjin,Shijiazhuang,Tangshan,Qinhuangdao,Baoding,Cangzhou,Chengde,Handan,Hengshui,Langfang,Xingtai,Zhangjiakou)

4.3.3. Projections of peak carbon emissions and time to peak

Based on the regression analysis and scenario parameters, the projected changes in carbon emissions for the 13 cities in the Beijing-Tianjin-Hebei region from 2023 to 2050 have been determined under three different scenarios, as shown in Fig.**8**. The future trajectory of carbon emissions in each city shows a trend of increasing and then decreasing. However, due to the differences in the economy, population, and energy resources of each city, the time and peak value of carbon reaching the peak are different. In the low carbon scenario, all cities have the lowest carbon emissions. The low carbon scenario is 1.96% to 3.16% lower than the baseline scenario carbon emissions on average, and the high carbon scenario is 1.58% to 3.66% higher than the baseline scenario carbon emissions on average. The seven cities of Tianjin, Tangshan, Baoding, Cangzhou, Chengde, Hengshui, and Langfang have large differences in carbon emissions among the three scenarios, and the carbon emissions of the low-carbon scenario are significantly lower than those of the baseline and high-carbon scenarios. Therefore, the governments of these 7 cities should pay attention to the values of the indicators of the low carbon scenario and make efforts to reach the set values of the indicators of the low carbon scenario. This can improve the efficiency of pollution reduction and carbon reduction. Baoding, Cangzhou, Chengde, Hengshui and Langfang are the 4 cities with larger peaks under the high carbon scenario, but at the same time, we find that the rate of carbon emission reduction after reaching the peak is also very fast. Therefore, these 4 cities should try to control the indicators when formulating policies to avoid being in the high carbon scenario. If they reach the high carbon scenario due to uncontrollable factors, they should reduce energy consumption and adjust their structure to reduce the peak.



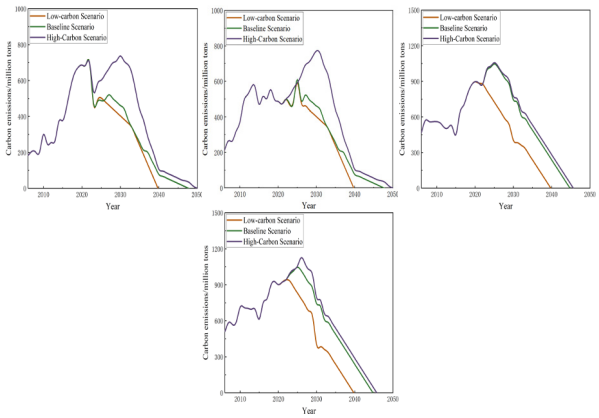


Fig.8. Results of carbon peaking projections for 13 cities(Beijing,Tianjin,Shijiazhuang,Tangshan,Qinhuangdao,Baoding,Cangzhou,Chengde,Handan,Hengshui,Langfang,Xingtai, Zhangjiakou)

In order to more visually compare the peak time, we compare the peak times of the 13 cities under the low carbon scenario, the baseline scenario, and the high carbon scenario, as shown in Fig.**9**. Under the baseline scenario, the cities can reach the peak between 2022 and 2035, and it is clear that most of the cities in the region under the baseline scenario can reach the goal of "Peak Carbon by 2030". The baseline scenario shows that most of the cities in the Beijing-Tianjin-Hebei region can reach the goal of "2030 carbon peak". Among them, Hengshui city reaches the peak at the earliest time, and Tangshan city reaches the peak at the latest time. Under the low carbon scenario, each city reaches the peak between 2022 and 2031. On average, each city in the Low Carbon Scenario peaks 2 years earlier than the Baseline Scenario. Like the baseline scenario, Hengshui City peaks the earliest, in 2022. Tangshan city peaks the latest, in 2031. In the high carbon scenario, the peak time for each city is concentrated in 2025-2037. On average, each city peaks 3 years later than the baseline scenario. Combining the forecast results and the peaking time, we can categorize the 13 cities into three types. The first category is peak-pioneer cities, i.e., the earliest carbon peak time. They include: Qinhuangdao, Baoding, Chengde, Hengshui, Langfang, Xingtai and Zhangjiakou. The second category is the Peak Optimistic Cities, i.e., although the time of reaching the peak is not as early as the Peak Pioneer Cities, as long as the development of each indicator is in accordance with the plan, the goal of "Peak Carbon 2030" can be realized. These cities include Shijiazhuang, Cangzhou and Handan. The last category is the Peak Catch-up Cities, i.e., they are late in reaching the peak and need to develop strong policies to catch up with the first two categories if they want to achieve the Peak Goal. These include: Beijing, Tianjin and Tangshan.

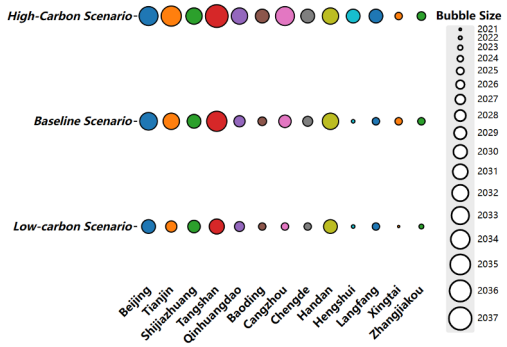


Fig.9. Comparison of Peak Reaching Time in 13 Cities in Beijing-Tianjin-Hebei

5 Discussion

(1)The carbon emission drivers and scenarios selected in this paper may not fully reflect the actual situation and future development trends in the Beijing-Tianjin-Hebei region. While the STIRPAT model is utilized to predict the peak value of carbon emissions and the timing of reaching this peak, it is important to note that predictions may not be entirely precise. Future studies can aim to enhance the accuracy of indicators to align more closely with the region's actual developmental dynamics.

(2)The data for the driver study were mainly from the statistical yearbook, and some drivers for which data were difficult to obtain were not considered. More influencing factors should be included in subsequent studies.

(3)The scales studied in this paper are municipal scales and should be expanded to the county level in future studies in order to make more accurate and targeted recommendations.

6 Conclusions

In order to achieve high-quality synergistic economic development in the Beijing-Tianjin-Hebei region, it is essential to prioritize the sustainable utilization of environmental resources and emphasize the importance of reducing pollution and carbon emissions. This study accurately illustrates the development trends and spatial distribution of carbon emissions in the region by analyzing data from 13 cities between 2006 and 2022. By utilizing the LMDI model, this study decomposes the drivers of carbon emissions from a static perspective. In order to analyze the trend in carbon emissions development and predict the timing of reaching peak carbon emissions from a dynamic viewpoint, the STIRPAT model is utilized. The goal is to contribute to the creation of environmentally sustainable development policies and initiatives, as well as the achievement of the "dual-carbon" goal in the Beijing-Tianjin-Hebei region. Key findings of this research include:

(1)During the period between 2006 and 2022, the total carbon emissions exhibited a fluctuating pattern, initially rising, then slightly dropping, and eventually increasing again to peak in 2022. In total, carbon emissions increased by 81.37%, climbing from 208,253,200 tons to 377,712,600 tons. The primary contributor to this increase was Beijing, followed by Tianjin, Tangshan, Shijiazhuang, and Handan. Combined, these cities reported a cumulative carbon emission of over 20,000,000 tons from 2006 to 2022, marking a significant milestone in carbon emissions for the Beijing-Tianjin-Hebei region.

In terms of spatial distribution, the Beijing-Tianjin-Hebei region follows a trend of "high carbon emissions in the central areas and lower emissions in the periphery." Beijing, Tianjin, and Tangshan consistently exhibit high levels of carbon emissions, whereas the surrounding cities generally have lower carbon emission levels. Cities like Hengshui, Cangzhou, and Xingtai demonstrate lower carbon emissions due to their less advanced industrial development, resulting in lower energy consumption and consequently reduced carbon emissions.

(2)Utilizing the LMDI model, carbon emission drivers were decomposed to distinguish between factors that promote and inhibit carbon emissions. The drivers that contribute to carbon emissions include the effects of economic development and population scale, while the factors that restrain carbon emissions consist of the energy structure effect. The impact of energy intensity effect varies over different years, sometimes promoting carbon emissions and other times inhibiting them. The relative importance of these four drivers in terms of their contributions is ranked as follows: economic development effect > energy intensity effect > energy structure effect > population size effect. Therefore, the Beijing-Tianjin-Hebei region should prioritize addressing the influence of economic development effect and energy intensity effect on carbon emissions. When examining the spatial dimension, it is evident that the contribution values of the drivers across the 13 cities exhibit significant disparities. In Beijing, Tianjin, and Tangshan, the economic development effect exerts the most substantial impact on carbon emissions. This is primarily due to the leading GDP levels in these cities within the Beijing-Tianjin-Hebei region, where the rise in economic development directly correlates with an increase in carbon emissions to a certain extent.

(3)In the 14th Five-Year Plan for the Beijing-Tianjin-Hebei region, there is a strong emphasis on the importance of ecological environment protection. This study utilizes the STIRPAT model and introduces urbanization rate and industrial structure as factors. By incorporating the policies and statistical data from Beijing-Tianjin-Hebei cities, the study forecasts the development trajectory of six variables and establishes three scenarios: low carbon, baseline, and high carbon scenarios. The analysis predicts the changing trend of carbon emissions and the timing of peak emissions for the 13 cities from a dynamic viewpoint. The projected future path of carbon emissions in each city demonstrates an initial increase followed by a decline. Under the baseline scenario, most cities are expected to reach their peak emissions between 2022 and 2035, indicating that they are on track to achieve the goal of "peak carbon emissions by 2030" under this scenario. In the low carbon scenario, each city is projected to reach

its peak between 2022 and 2031, on average 2 years earlier than in the baseline scenario. The low carbon scenario is estimated to be 1.96% to 3.16% lower than the baseline scenario. Conversely, the high carbon scenario suggests that cities will peak between 2025 and 2037, on average 3 years later than the baseline scenario, with carbon emissions averaging 1.58% to 3.66% higher than the baseline scenario. Therefore, for a comprehensive strategy, the Beijing-Tianjin-Hebei region should aim to achieve the low-carbon scenario to meet the target of "Peak Carbon by 2030".

7 Suggestions

(1) Leveraging the city cluster effect for the development of a sustainable economy. The Beijing-Tianjin-Hebei region should center around Beijing, fully utilize the radiation-driven role of core cities in the urban agglomeration, and facilitate the transition of the economy towards low-carbon and energy-efficient practices. Analysis of the LMDI drivers decomposition indicates that economic development is the primary positive factor driving carbon emissions. Therefore, Beijing-Tianjin-Hebei needs to shift away from the model of "economic growth at the expense of the environment" and embrace the development of a sustainable green economy. Positioned as one of the most dynamic city clusters in China, Beijing-Tianjin-Hebei should maximize its synergistic development potential. Government departments in each city should take the lead, considering factors such as economic status, environmental conditions, resource allocation, and strategic positioning to establish a framework for energy conservation and emission reduction responsibilities, thereby collectively advancing the initiatives for energy efficiency and emission reduction in the Beijing-Tianjin-Hebei region.

(2) Modifying the energy structure to utilize more sustainable energy sources. The impact of energy structure is also a significant driver leading to the rise in carbon emissions. Hence, the Beijing-Tianjin-Hebei region should consistently enhance the optimization of its energy consumption structure, decrease the reliance on coal, and actively promote the adoption of clean energy sources like wind, solar, and biomass energy. Cities within the Beijing-Tianjin-Hebei region, particularly Tangshan and Beijing, need to promptly restructure their energy consumption patterns to establish a balanced and scientifically diversified energy mix.

(3) Encourage the modernization of conventional sectors and the growth of emerging industries. Based on the STIRPAT model fitting outcomes, it has been identified that a reduction in the proportion of secondary industry can effectively lower carbon emissions in the Beijing-Tianjin-Hebei region. Therefore, it is imperative for the region to expedite the phasing out of outdated production capacities and address issues related to excess production capacity. Beijing, Tianjin, Shijiazhuang, and Handan should leverage their distinctive cultural assets to establish modern service sectors characterized by ecological and cultural attributes. Additionally, in the age of rapid Internet advancement, cities in the Beijing-Tianjin-Hebei region should foster the growth of low-carbon industries like the Internet, big data, and finance, with Beijing taking the lead as a major urban center.

(4)Promote the adoption of a low-carbon lifestyle and establish a low-carbon community. As the economy continues to advance, individuals are demanding better living conditions. Hence, it is crucial to promote low-carbon consumption and eco-friendly transportation without compromising people's quality of life. Local authorities must intensify efforts in raising awareness about climate change through enhanced public campaigns and educational initiatives. Various events should be organized to spread knowledge about low-carbon practices and boost public consciousness regarding low-carbon living, all while maintaining the essence of the original message.

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