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Spatial and Temporal Evolution of Synergistic Effect between Reduction of Pollution and Carbon in China

-- Analysis based on Total Fossil Energy Consumption

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Abstract

Synergistic effect between reduction of pollution and carbon in China including 30 provinces, eight economic zones from 2012 to 2021, is firstly measured based on Coupled Coordination Model by this paper. Total energy consumption, energy consumption structure, regional industrial structure, urbanization rate, per capita GDP, total import and export trade as its indicators and then their impacts on synergistic effect is examined with Ordinary Least Squares, and the strength of impact of the influencing factors are finally analyzed through spatial-temporal geographical weighted regression model (GTWR) followed by the examination of spatial heterogeneity of selected indicators through Moran's I Index. Conclusions include: (1)The reduction of pollutant emissions has witnessed rapid progress, while the decrease in carbon dioxide emissions has been comparatively slower. In terms of synergistic effects, China's overall synergy between pollution and carbon reduction has consistently improved from 2012 to 2021. (2) As for the influencing effects, total energy consumption and per capita GDP negatively hinder the synergistic effect between reduction of pollution and carbon in most provinces, while others positively promote the achievement of the synergistic effect between reduction of pollution and carbon. Suggestions includes provincial development strategies, industrial structure optimization and clean energy strategies.

Keywords

Reduction of Pollution and Carbon; Synergistic Effect; Influencing Factors; Coupled Coordination Model; GTWR Model.

1. Introduction

1.1 Problem Formulation

With the continuous advancement of the national economy, there is an ongoing enhancement in people's demands for high-quality living standards, while concurrently witnessing a heightened government focus on environmental concerns. Amidst the growing threats posed by climate change, the overarching goal of the Paris Agreement is to cap the rise in global mean temperature above pre-industrial levels at a maximum of 2 degrees Celsius, with an aspirational target of 1.5 degrees Celsius. At the 75th United Nations General Assembly, The Chinese administration has pledged to reach the zenith of carbon dioxide emissions by the year 2030 and is dedicated to attaining the objective of carbon neutrality by 2060.[1]. On June 13, 2022, a joint notice was issued by the Ministry of Ecology and Environment of China, in collaboration with additional pertinent agencies. This notice emphasizes the importance of implementing the Pollution and Carbon Reduction Synergy Implementation Plan as a fundamental approach to drive comprehensive green transformation in economic and social development. To improve the quality of China's atmospheric environment, the Action Plan for the Prevention and Control of Air Pollution[2]and the Three-year Action Plan for Winning the Battle against Blue Skies[3] has been successively issued by The State Council of China, these plans have significantly improved the air environmental quality in China. In 2021, approximately 64.3% of urban areas complied with air quality standards. However, a significant portion, over one-third, did not achieve compliance. Thus, the challenge of mitigating air pollution remains significant.

According to the Implementation Plan for Synergistic Efficiency of Pollution Reduction and Carbon Reduction, environmental pollutants and carbon emissions are highly rooted and of the same origin[4]. The discharge of atmospheric pollutants and greenhouse gases, including carbon dioxide, share a common root, origin, and process were pointed out by Yi Lan[5]. Based on the data from 2011 to 2020, Liu Maohui et al.[6]employed the STIRPAT model to identify that the primary sources of carbon dioxide and air pollutants are the combustion of fossil fuels associated with human industrial and domestic activities, and their main emission sources are industrial, accounting for 58.6%-76.7%.Wang Li et al.[7] took Weinan City as an example and analysed the impact of pollution reduction, energy structure and industrial structure adjustment policies on the future energy consumption and air pollutant emission reduction potential of Weinan City based on the LEAP model. The research concludes that enhancements in energy structure, industrial restructuring, and transportation adjustments exert significant synergistic effects on the reduction of both air pollutants and greenhouse gases. Consequently, achieving the dual reduction of pollution and carbon emissions is theoretically viable. Based on the air pollution emissions and carbon dioxide emissions data of China’s 30 provinces, in each province coupled coordination model had been used to classify the synergistic effect between reduction of pollution and carbon and dissects the determinants and spatial variations of the synergistic effect based on the GTWR model. It is expected to provide theoretical support and policy reference for achieving carbon peak, carbon neutrality through the synergistic effect between reduction of pollution and carbon.

1.2 Literature Review

In the research on carbon reduction, many scholars put forward effective paths for carbon reduction based on the provincial level. Miao et al.[8] selected Jiangsu Province as the research object and proposed that guiding economically developed areas to take the lead in achieving carbon peak within the provincial scope is an effective way to achieve China's carbon peak goal quickly and efficiently. Ding Yinhui and Yang Yaru[9] evaluated the potential of China's provinces to reduce carbon emissions between 2011 and 2020 and found that eastern provinces had a dominant role in promoting joint emission reduction across the country, while western provinces had a relatively limited impact. In the literature on pollution reduction, many scholars have found that digital development has a certain impact on pollutant emissions. Wang Fang et al.[10] found through research that the digital economy may aggravate environmental pollution in the early stage of development, but it will help reduce environmental pollution as time goes by. And synergy effect refers to the result due to synergy. In other words, it refers to the aggregate or composite effect that emerges from the interplay among numerous subsystems within a complex, open system. Swart R et al.[11] highlighted that air pollutants and greenhouse gases share characteristics of a common root, origin, and process. In addition, a large amount of carbon dioxide will also be emitted during the terminal treatment process of air pollution, so there is a certain interaction between air pollution and carbon dioxide[12] .Therefore, there is a certain interaction between air pollution and carbon dioxide.Tang Xiangbo et al.[13] posited that carbon emission reduction and air pollutant control are distinct yet interrelated subsystems within a single overarching system, and the synergistic effect between reduction of pollution and carbon refers to the synergistic development trend of interaction between the two. This paper defines the coupling coordination degree of reduction of pollution and carbon as such.

Given the persistent severity of air pollution, there is a burgeoning focus on analyzing the factors influencing the synergistic effect between reduction of pollution and carbon. Consequently, research is increasingly directed towards examining the determinants and implementation pathways for achieving synergies in reduction of pollution and carbon within China. Yu Yaguai et al.[14] employed the LMDI model to analyze the determinants of carbon emissions, identifying the suppressive and enhancing impacts of production efficiency and economic growth on the carbon dioxide emissions associated with pig farming. From the perspective of quantitative analysis, based on LMDI and coupled coordination models, Wang Fengting et al.[15] dissected the decoupling elasticity between carbon dioxide emissions and economic growth into distinct components, such as carbon emission intensity, industrial structure, and so on. Based on the three-stage DEA and system GMM method, Yu Yaguai et al.[16] assessed the carbon neutrality trajectory of publicly traded construction firms, utilizing green financing-related factors as input indicators and economic and environmental outcomes as output indicators. Based on the STIRPAT model, Wang Libin and Zhang Yun[17] and Liu Maohui et al.[6] used indicators such as energy intensity, carbon dioxide emission intensity and total population to measure the synergistic effect between reduction of pollution and carbon in China and Tianjin. Lin Boqiang and Zhu Junpeng[18] and Chen Weiming and Kim Hana[1] and Feng Peijiong et al.[20] used the STIRPAT model to properly decompose environmental impact factors and compare the impact level of different factors on the environment. This model has gained widespread adoption for predicting pollutant and carbon dioxide emissions, attributed to its superior analytical capabilities over traditional models. Zhao Litong et al.[21] andYu Yaguai et al.[16] pointed out that industrial structure, population, economy and urbanization rate have important impacts on the acceleration of carbon peak and need to be adjusted appropriately.

In examining the factors influencing the synergistic effect between reduction of pollution and carbon, scholars have underscored the significance of spatial-temporal distribution in their analyses. Tang Xiangbo et al.[13] applied the GTWR model and discovered significant spatial clustering of air pollutants and carbon dioxide emissions, particularly in regions characterized by economic development, high population density, and substantial energy consumption. Xu Zanzan and Yu Yaguai[22] found that there was a substantial negative correlation between the spatial clustering of pollutants and carbon dioxide emissions and the intensity of environmental regulation and the degree of economic openness. Conversely, a significant positive correlation was observed with the level of government support, the structure of industry, and urban economic growth.

In conclusion, both domestic and international scholars have conducted extensive research on the factor analysis and spatial-temporal distribution of the synergistic effect between pollution reduction and carbon mitigation, yielding significant outcomes that form a robust theoretical foundation for this study. Despite this, the literature has yet to fully embody the impact of total fossil energy consumption on the synergistic effect. The emissions from fossil fuel use are substantial.In 2021, the total amount of sulfur dioxide emissions, nitrogen oxide emissions and particulate matter emissions in China will reach 2096584, 3688711 and 3252712 tons respectively, and the emission equivalent of carbon dioxide will reach 2329278 million tons. Given China's urgent need to achieve carbon peak and neutrality goals, this study employs data from 30 provinces in China from 2012 to 2021. Utilizing a coupled coordination model to assess the synergistic effect at the national and provincial levels, and the GTWR model, the paper investigates the influencing factors and spatial-temporal distribution of the synergistic effect. The aim is to offer actionable policy recommendations to facilitate the attainment of China's strategic objectives for carbon peak and carbon neutrality.

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2. Materials and Methods

2.1 Definition of Core Concepts

The Implementation Plan for Synergistic Efficiency of Pollution Reduction and Carbon Reduction advocates for the concurrent reduction of environmental pollutants and carbon emissions, with the dual objectives of fostering a 'Beautiful China' and realizing carbon peaking and neutrality. Carbon peaking signifies the pinnacle of carbon dioxide emissions, after which a reduction is anticipated. Carbon neutrality, conversely, pertains to the state where factitious carbon dioxide emissions over a specific period-typically a year-are counterbalanced by carbon sequestration measures, such as afforestation, resulting in a net-zero carbon dioxide footprint. The plan advocates a transition to a green and low-carbon energy system, incrementally elevating the proportion of non-fossil energy in total consumption and synchronizing emission reductions across various environmental sectors, notably greenhouse gases. Greenhouse gases encompass water vapor, carbon dioxide, ozone, and methane, with carbon dioxide constituting approximately 26% of the total emissions. In light of the objectives for carbon peaking and neutrality, this study focuses on carbon dioxide emissions as the principal indicator for carbon emissions.

China's industrial sector is not only a major consumer of traditional energy but also the main source of carbon dioxide emissions. Industrial pollutants-such as wastewater, gas emissions, solid waste, and noise-are significant contributors to environmental degradation, with total emissions on the rise. Due to the colorless and odorless nature of carbon dioxide under standard conditions, industrial waste gas is used as a proxy for environmental pollutant measurements in this study to enhance comparability and facilitate the calculation of synergistic effects.

Greenhouse gases and air pollutants are primarily generated through the combustion of fossil fuels[23]. In 2021, raw coal(55.9%), coke(8.87%), gasoline(2.71%), diesel(2.89%), and natural gas(8.8%) accounted for significant shares of total energy consumption. Hence, this study identifies raw coal, coke, gasoline, diesel, and natural gas as key indicators for assessing fossil energy consumption.

2.2 Calculation of Pollutant Emission Equivalent

Due to the legal requirement by the Ministry of Ecology and Environment in 2015, preliminary data on pollution sources for the years 2016-2020 were updated. As a result, there are differences in the pollution source data before and after 2016, making the emissions data for pollutants after 2016 not directly comparable with previous years.

To comprehensively compare the industrial exhaust emissions across different regions in the same year and within the same region across different years, this paper calculates the emissions equivalents of industrial exhaust for 30 provinces in China from 2011 to 2020. The calculations are based on the atmospheric pollutant equivalence coefficients specified in the "Environmental Protection Tax Law." The calculation method is shown in Formula 1:

$$E = \alpha Q_{SO_2} + \beta Q_{NO_X} + \gamma Q_{PM} \quad (1)$$

Table 1. Pollutant values of sulfur dioxide, nitrogen oxides and smoke (powder) dust

Type of pollutant	Equivalent value of pollutants (kg)
sulfur dioxide	0.95
nitrogen oxide	0.95
smoke (powder) dust	2.18

In Formula (1), E represents pollutant emission equivalent; α, β, γ represent the coefficients of converting SO_2, NO_X, PM into pollutant equivalent,that is, the inverse of the pollution equivalent value; Q_{SO_2}, Q_{NO_X}, Q_{PM} represent the emissions of SO_2, NO_X, PM, the unit is 10^3 kg. To calculate the industrial waste gas emission equivalent, the specific values of pollutant equivalent values are shown in Table 1.

2.3 Measurement of Carbon Dioxide Emissions

Since our country has not directly published carbon dioxide emission data at present, this paper focuses on five types of fossil fuels—raw coal, coke, gasoline, diesel, and natural gas—to assess carbon dioxide emissions. This paper refer to the relevant parameters recommended in the Guidelines for Upgrading the Preparation of Greenhouse Gas Inventory (Trial) to conduct the carbon emission in 30 provinces in China from 2012 to 2021 (Formula 2):

$$CE_i = \sum_i E_{ij} \times EF_j \quad (2)$$

In Formula 2, CE_i represents the carbon dioxide in the ith province; E_{ij} represents the physical consumption of the jth energy in the ith province in m³, kg or L, and EF_j represents carbon dioxide emission factor of the jth energy; Carbon dioxide emission factor=carbon emission factor ×low calorific value of energy×10^(-6)×(44/12)×carbon oxidation rate, and the calculation parameters are shown in Table 2.

Table 2. Carbon dioxide emission calculation parameters

Energy types	Low calorific value of energy(kJ/kg)	Carbon oxidation rate	Carbon emission factor(tC/TJ)	CO2 emission factor (kg-CO2/kg)
Raw coal	20908	0.94	26.37	1.9003
Coke	28435	0.93	29.5	2.8604
gasoline	43070	0.98	18.9	2.9251
Diesel oil	42652	0.98	20.2	3.0959
Natural gas	38931	0.99	15.3	2.1621

2.4 Calculation of the Synergistic Effect between Reduction of Pollution and Carbon

Regarding the analysis of the synergistic effect between reduction of pollution and carbon, the existing research includes the relationship between energy carbon emissions and economic growth[23], carbon emission scenario analysis and prediction[6], technical support for pollution reduction and carbon reduction[15], etc. From the perspective of research methods, common methods to predict the synergistic effect between reduction of pollution and carbon include the environmental impact assessment model method with extensible randomness, the Decoupling model method[23], long-term energy substitution planning system model method[7], Theil Index Model[25],etc.

The coupling coordination model provides a quantitative measure of the synergy between the reduction of pollutants and greenhouse gas emissions, referring to the coupling coordination model,this paper defines the expression of the synergistic effect (Formula 3) as follows:

$$C = \sqrt{\frac{U_1 U_2}{\left(\frac{U_1+U_2}{2}\right)^2}} = \frac{2\sqrt{U_1 U_2}}{U_1+U_2} \quad (3)$$

$$T=aU_1+bU_2 \tag{4}$$

$$D=\sqrt{C \times T} \tag{5}$$

U1 and U2 denote the levels of the carbon emission reduction and air pollution control systems, and are represented by the standardized value of carbon emissions and pollutant emission equivalent, respectively. The purpose of the range standardized treatment of the two is to eliminate the influence of dimension. Since the numerical values of 0 and 1 must appear in the calculation process of range standardization, the overall translation of the standardized data is carried out in this paper, and the translation range is 0.001 to avoid the problem of no solution in the calculation process; C represents the coupling degree of the two systems; T represents the comprehensive coordination index; a and b represent coefficients to be determined. This paper believes that carbon emission reduction is as important as air pollutant control, that is, a=b=0.5; D represents the coupling coordination degree of pollution and carbon reduction, ranging from [0,1]. The closer D value is to 1, the better and stronger the coordination between carbon emission reduction and air pollutant control system is. As for the classification criteria of coupling degree and coupling coordination degree, referring to the research of Li Yunyan and Du Wenxin[26], the coupling coordination level calculated according to Formula 3-5 can be divided into four categories (Table 3): incoordination decline, excessive coordination, low-degree coordination and high-degree coordination.

Table 3. Coupling coordination level division criteria

Serial number	Degree of coupling coordination (D)	Correlated state	Coordinated development stage
1	$0<D\leq 0.1$	Extreme dissonance	degenerating stage
2	$0.1<D\leq 0.2$	Serious dissonance	
3	$0.2<D\leq 0.3$	Moderate dissonance	acceptable period of dissonance
4	$0.3<D\leq 0.4$	Mild dissonance	
5	$0.4<D\leq 0.5$	On the verge of disorder	transitional period
6	$0.5<D\leq 0.6$	Barely in tune	
7	$0.6<D\leq 0.7$	Primary coordination	evolution period
8	$0.7<D\leq 0.8$	Intermediate coordination	
9	$0.8<D\leq 0.9$	Good coordination	period of high coordination
10	$0.9<D\leq 1.0$	Quality coordination	

2.5 Spatial-temporal and Geographical Weighted Regression Model of the Synergistic Effect between Reduction of Pollution and Carbon

Geographically and Temporally Weighted Regression can consider the influencing factors of the synergistic effect between reduction of pollution and carbon at different time points under the characteristics of non-stationarity and heterogeneity in complex space. For each observed spatial unit, the GTWR model can perform local regression on it at different time points, to reflect the effect of the selected index at different time points and different spatial locations. Therefore, the GTWR model can be used to analyze the spatial heterogeneity of the factors affecting the synergistic effect. The expression of the GTWR model (Formula 4) is:

$$Y_i = \beta_0(u_i, v_i, t_i) + \sum_{k=1}^{n} \beta_k (u_i, v_i, t_i) x_{ik} + \varepsilon_i \quad (6)$$

Y_i is the synergistic effect of province i; β_0 is a constant term; (u_i, v_i, t_i) is the spatial-temporal coordinates of province i; β_k is the regression coefficient of the kth influencing factor of the synergistic effect between reduction of pollution and carbon in province i; n is the number of spatial locations; x_{ik} is the kth influencing factor of the synergistic effect between reduction of pollution and carbon in province i; ε_i is the random error term of province i.

2.6 Selection of Influencing Factors of the Synergistic Effect between Reduction of Pollution and Carbon

When constructing the index system of influencing factors for pollution reduction and carbon reduction, we draw on the results of previous research, fully consider the influencing factors of carbon dioxide and industrial waste gas emissions, and give consideration to the scientific nature of indicators and the availability of data. The indicators of the synergistic effect between reduction of pollution and carbon include energy consumption level, regional industrial structure, economic development level and opening up level.

In terms of energy consumption level[27], the combined energy consumption from raw coal, coke, gasoline, diesel, and natural gas is designated as the total energy consumption, while the proportion of natural gas within the total energy mix serves as an indicator of the energy consumption structure. Since the energy standard adopted in China is standard coal, this paper converts each energy into standard coal consumption when calculating the total energy consumption. The regional industrial structure is quantified by the ratio of industrial added value to the GDP. In terms of the level of economic development, GDP per capita and urbanization rate are used as measures. In terms of the level of opening-up, we draw on the ideas of Tang Xiangbo et al.[13] and choose the total import and export of goods as the measurement standard of the total import and export trade. The detailed index system is shown in Table 4.

Table 4. Index system of influencing factors of the synergistic effect between reduction of pollution and carbon

Primary index	Secondary indicators	Units
Energy consumption level	Total energy consumption	10^4t tce
	Energy consumption structure	%
Regional industrial structure	Industrial value added as a percentage of GDP	%
Level of economic development	GDP per capita	10,000 Yuan per person
	Urbanization rate	%
Level of opening up	Total import and export trade	10,000 Yuan

In summary, this paper designates the coupling coordination degree of pollution and carbon reduction as the dependent variable. It identifies total energy consumption as the primary independent variable. Additionally, the energy consumption structure, regional industrial structure, per capita GDP, urbanization rate, and total import and export trade are considered as control variables.

2.7 Sample Selection and Data Sources

This paper selects the sample data of Chinese provinces from 2012 to 2021 (excluding the data from Hong Kong, Macao, Taiwan and Tibet Autonomous Region) for research. The industrial waste gas data are from Table 4-1 of the China Statistical Yearbook on Environment, and the low calorific value

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of energy is from China Energy Statistical Yearbook 2018, and the carbon emission coefficient and carbon oxidation rate are from Provincial Greenhouse Gas Inventory Compilation Guide (Trial) (2011), and the data on GDP, population proportion, and the added value of the secondary industry are from the China Statistical Yearbook and the National Bureau of Statistics.

3. Results

3.1 Spatial Differentiation of Industrial Waste Gas and Carbon Dioxide Emissions: 2011-2020

The changes in the total pollutant emission equivalent and carbon dioxide emissions in China from 2012 to 2021 are illustrated in Figure 1. As illustrated, there was a gradual decline in carbon dioxide emissions during the specified period, reduced to 2.329 billion tons in 2020, from 3.020 billion tons in 2012, which corresponds to a reduction rate of 29.64%. Pollutant emission equivalents began to significantly decline in 2014, after a slow reduction between 2012 and 2014, from 42.292 million tons to 39.777 million tons. However, from 2014 to 2021, the reduction in pollutant emissions was significant, with an 80.94% decrease by 2021 compared to 2014. This indicates that while China made remarkable progress in controlling air pollution during the 13th Five-Year Plan period, similar progress was not achieved in reducing carbon dioxide emissions.

As seen in Figure 1, the equivalent of industrial waste gas emissions also showed a clear downward trend. According to estimates from the World Health Organization, outdoor fine particulate pollution in China causes more than one million premature deaths annually. To improve air quality and safeguard public health, China implemented the Air Pollution Prevention and Control Plan in 2013, which introduced a series of stringent control measures. By 2019, inspections revealed that the average concentration of fine particulate matter in China had decreased by 44% compared to 2013 levels, which contributed significantly to the pollutant emission equivalent's reduction. From 2012 to 2021, however, carbon dioxide emissions declined at a slower rate. According to data from China's seventh national population census, the population reached 1.412 billion in 2021, an increase of 58.41 million from 1.354 billion in 2012. Carbon dioxide is emitted through various human activities, including daily life, production, and business operations.

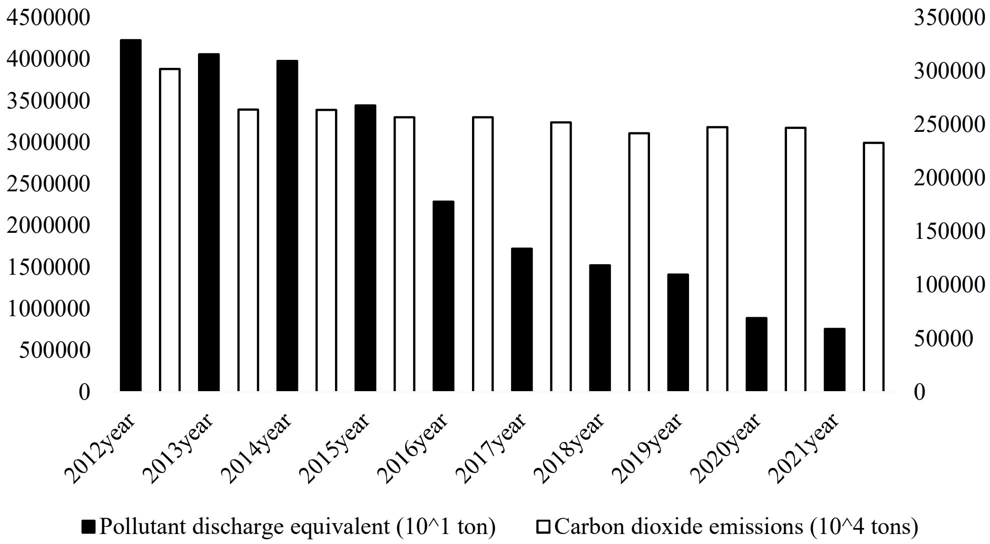

Figure 1. Time change characteristics of pollutant emission equivalent and carbon dioxide emissions in China during 2012-2021

The spatial characteristics of pollutant emission equivalents and carbon dioxide emissions across 30 provinces in China from 2012 to 2021 are illustrated in Figures 2 and 3. As shown in Figure 2, in 2012, carbon dioxide emissions were notably higher in Shandong, Hebei, Shanxi, Liaoning, and Inner

Mongolia, while emissions were comparatively lower in Jiangxi, Hainan, and Yunnan, indicating a trend of gradual decline from north to south. Conversely, the pollutant emission equivalents were elevated in Shandong, Henan, Hebei, Jiangsu, and Hunan, but lower in Qinghai, Ningxia, Xinjiang, and Yunnan, demonstrating a gradual decrease from east to west.

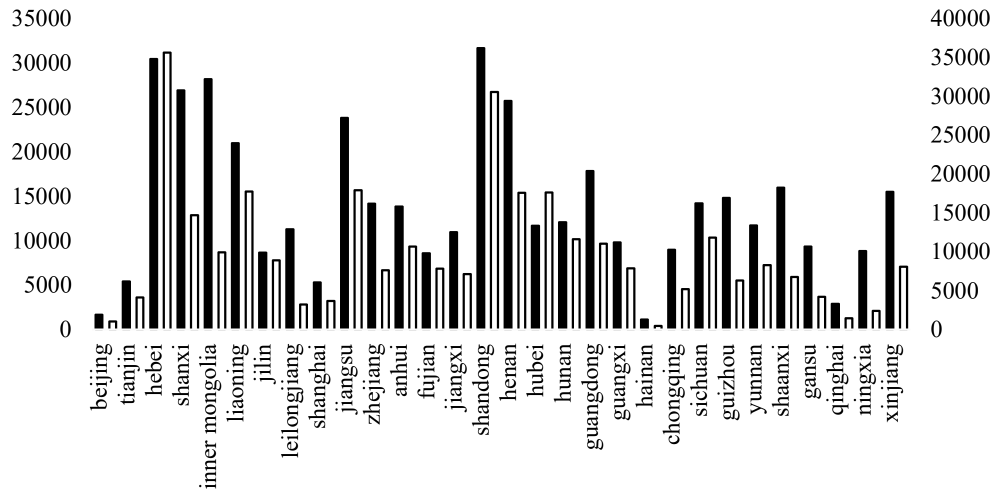

Figure 2. Spatial change characteristics of pollutant emission equivalent and carbon dioxide emissions of each province in 2012

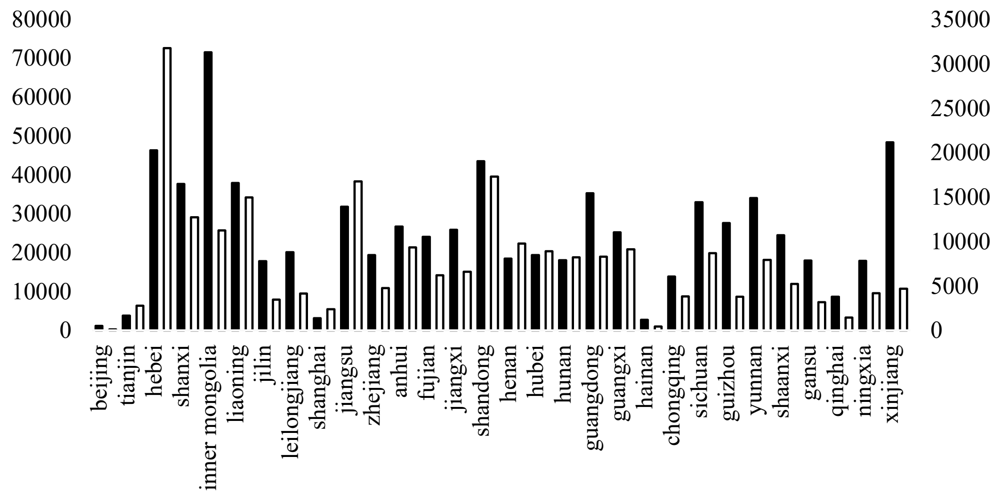

Figure 3. Spatial change characteristics of pollutant emission equivalent and carbon dioxide emissions of each province in 2021

Figure 3 illustrates that in 2021, carbon dioxide emissions were notably higher in regions such as Shandong, Guangdong, Shanxi, Shaanxi, and Xinjiang, while lower levels were observed in Jiangxi, Hainan, Yunnan, and Qinghai. This pattern reflects the characteristics of "high emissions in the north and south, low emissions in the middle." In contrast, pollutant emission equivalents were elevated in Inner Mongolia, Yunnan, Shaanxi, and Xinjiang, but lower in Jilin, Heilongjiang, Beijing, and Hainan, demonstrating a gradual decline "from west to east." According to Figures 2 and 3, carbon dioxide emissions have remained consistently low in Beijing, Tianjin, Shanghai, Hainan, and Qinghai. Beijing, Tianjin, and Shanghai exhibit strong economic vitality. Since the reform and opening up, Shanghai has emphasized adjusting its economic structure and transforming its mode of economic development, vigorously pursuing reforms, openings, and independent innovation. In 1993, Hainan Province adjusted its industrial development strategy from accelerating secondary industry growth to prioritizing the advancement of the tertiary industry, which produces relatively fewer pollutants and carbon dioxide emissions.

3.2 Spatial Differentiation of Industrial Exhaust Gases and Carbon Dioxide Emission Factors: Interprovincial Analysis

Figure 4 illustrates the coupling coordination degree of pollution and carbon reduction across 30 provinces in China from 2012 to 2021. Over this period, the average values of both the coupling degree and the coupling coordination degree exhibited an overall upward trend with fluctuations, peaking in 2021. This suggests an intensifying synergy between carbon emission reduction and air pollutant control systems. Based on the variations in the coupling coordination degree, the relationship between the two control system from 2012 to 2021 can be categorized into three stages: ①From 2012 to 2014, the coupling coordination degree was in an intermediate coordination state, with a slow increase of 3.84%;② From 2015 to 2017, the coupling coordination degree transitioned to a good coordination state, moving from the development phase to the advanced coordination phase, characterized by rapid growth; ③ From 2018 to 2021, the coupling coordination degree reached a high-quality coordination state, although it experienced slight fluctuations and a decline in 2018. According to a survey by the Rocky Mountain Institute in the United States, global carbon emissions increased by approximately 2% in 2018, primarily due to steady coal consumption growth and rising use of oil and natural gas. Emissions have risen in nearly all countries. Overall, the coupling and coordination degree of China's manufacturing industry has shown a consistent upward trajectory.

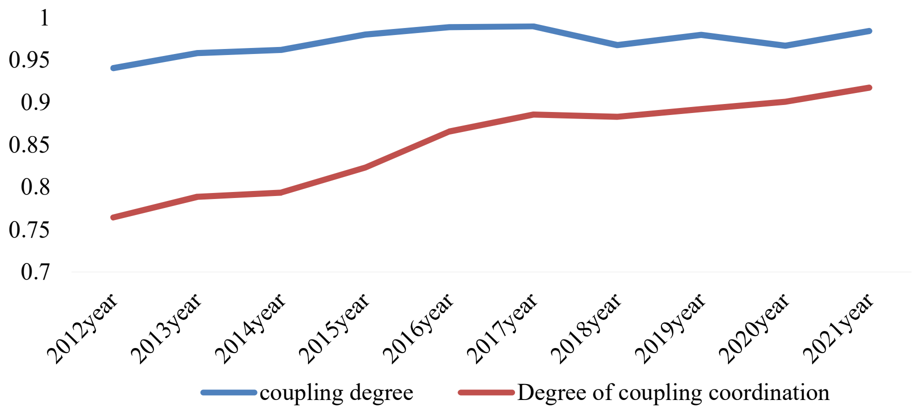

Figure 4. Changes in the average value of coupling degree and coupling coordination degree of pollution reduction and carbon reduction in China from 2012 to 2021

The aggregate fluctuations in China's pollution and carbon reduction coupling coordination degree are not readily discernible. Thus, it is essential to further investigate the inter-provincial synergistic effects of pollutants and carbon dioxide across different provinces, as shown in Table5. From 2012 to 2020, two distinct characteristics emerged: solid and dynamic changes in the coupling coordination degree across 30 provinces.The solid characteristic indicates that a few provinces consistently maintained the same coupling coordination state from 2012 to 2021. For example, Beijing, Tianjin, Shanghai, Hainan, Qinghai, and Ningxia remained in a period of high coordination. In contrast, the dynamic changes reveal that from 2012 to 2021, most provinces experienced an increase in their coupling coordination degree. Notably, the number of provinces in decline-specifically those in extreme and serious coordination states-has decreased. Additionally, the provinces categorized under acceptable period of dissonance (i.e., moderate and mild dissonance) have dropped to zero, while only one province, Hebei, remains in the transition phase. Hebei Province has consistently exhibited low coupling coordination in pollution reduction and carbon reduction. Hebei's economic structure heavily relies on heavy industry, leading to severe environmental issues due to excessive resource and energy consumption. Moreover, some enterprises have inadequate awareness of environmental protection and insufficient pollution treatment facilities, exacerbating pollution. In response, the Hebei provincial government has implemented various policies for air pollution prevention and control, such as the "Hebei Province Air Pollution Prevention and Control Action Plan." This plan outlines specific objectives, tasks, and measures, providing a legal framework for improving air quality. Furthermore, Hebei offers financial subsidies, tax incentives, and other support for pollution control projects, encouraging enterprises to increase their environmental protection investments and to promote industrial transformation.

Table 5. Distribution of coupling coordination degrees between pollutants and carbon dioxide reduction in each province from 2012 to 2021

Province	2012year	2017year	2021year
Beijing	10	10	10
Tianjin	10	10	10
Hebei	2	6	6
Shanxi	6	9	9
Inner Mongolia	6	9	9
Liaoning	7	9	9
Jilin	9	10	10
Heilongjiang	9	10	10
Shanghai	10	10	10
Jiangsu	6	8	9
Zhejiang	9	10	10
Anhui	8	9	10
Fujian	9	10	10
Jiangxi	9	9	10
Shandong	2	8	9
Henan	6	9	10
Hubei	8	9	10
Hunan	9	9	10
Guangdong	8	9	10
Guangxi	9	10	10
Hainan	10	10	10
Chongqing	9	10	10
Sichuan	8	9	10
Guizhou	9	10	10
Yunnan	9	9	10
Shaanxi	8	10	10
Gansu	9	10	10
Qinghai	10	10	10
Ningxia	10	10	10
Xinjiang	8	9	10

Note: The number represents the serial number of coupling coordination degree

The number of provinces in both the period of high coordination and evolution coordination increased, suggesting an enhanced interplay between the two control systems. Inner Mongolia, for instance, progressed from a state of barely coordination to good coordination from 2012 to 2021, while Xinjiang transitioned from an intermediate coordination state to a quality coordination state. Since the 18th National Congress of the Communist Party of China in 2012, Inner Mongolia has made significant strides in ecological protection, pollution control, and transformation efforts, achieving notable success in afforestation and desertification control. By 2022, Inner Mongolia's installed new energy capacity reached 56 million kW, ranking first in China for new energy power generation. Beijing and Qinghai Province have also maintained high-quality coordination from 2012 to 2021. The Beijing government has implemented strict measures to tackle air pollution at its source, including controlling emissions from coal-fired boilers, industrial sources, and motor vehicles, promoting clean energy, optimizing industrial structures, and reducing pollutant output. A citywide campaign has been launched to eliminate coal-fired boilers, replacing many with gas-fired alternatives to reduce emissions of pollutants like sulfur dioxide and nitrogen oxides. In Qinghai Province, a wide array of clean energy resources-including solar, hydro, and wind energy-are developed comprehensively, significantly reducing fossil fuel consumption and emissions. Xinjiang Uygur Autonomous Region has a lower population density than other provinces, experiences less pollution and carbon dioxide emissions, contributing to its relatively favorable coordinated development stage. Overall, adjusting the industrial structure and implementing other measures could enhance Xinjiang's coupling coordination degree, ultimately leading to reduced emissions of pollutants and carbon dioxide.

Overall, from 2012 to 2021, the number of provinces exhibiting good and high-quality coordination gradually increased, accounting for two-thirds or more of all provinces in China. This rising coupling and coordination degree indicates progress in promoting reduction of pollution and carbon across the country. However, some provinces have not consistently reduced carbon dioxide emissions; for instance, Hebei Province experienced an increase in CO2 emissions in 2018. To improve the coupling and coordination degree, a reduction in carbon dioxide emissions is essential. This necessitates that the government formulate more reasonable and targeted policies and strategies tailored to local conditions to enhance the synergistic effect between reduction of pollution and carbon.

3.3 Spatial Differentiation of Industrial Waste Gas and Carbon Dioxide Emission: Eight Economic Zones

Table 6. Coupling and coordination degree of carbon emission reduction and air pollutant control systems in eight economic zones from 2012 to 2021

Year	Southern coastal Economic Zone	Eastern coastal economic zone	Northern coastal Economic zone	Northeast economic zone	Middle reaches of the Yangtze River Economic Zone	Middle Yellow River Economic Zone	Southwest Economic Zone	Northwest Economic Zone
2012	0.9075	0.8074	0.1319	0.8128	0.6857	0.1400	0.6879	0.8894
2013	0.9259	0.8237	0.4066	0.8362	0.7577	0.3808	0.7250	0.8920
2014	0.9238	0.8270	0.3868	0.8329	0.7543	0.4638	0.7402	0.8939
2015	0.9302	0.8446	0.5362	0.8625	0.7612	0.5849	0.7765	0.9111
2016	0.9441	0.8851	0.6388	0.9102	0.7746	0.7293	0.8285	0.9455
2017	0.9628	0.9128	0.6983	0.9197	0.7922	0.7936	0.8405	0.9471
2018	0.9655	0.9289	0.6689	0.9289	0.8486	0.8134	0.8453	0.9632
2019	0.9624	0.9227	0.6886	0.9206	0.8561	0.8096	0.8505	0.9618
2020	0.9802	0.9462	0.6702	0.9395	0.8861	0.8168	0.8643	0.9885
2021	0.9904	0.9504	0.7517	0.9514	0.8920	0.8397	0.8784	0.9880

To delve deeper into the regional spatial-temporal dynamics of the coupling coordination degree between carbon emission reduction and air pollutant control systems, this paper analyzes the synergistic effect based on the eight economic zones to clarify the differences in each economic zone. Based on the analysis of the eight economic zones, pollutants and carbon dioxide emissions are mainly concentrated in the Southern Coastal, the Middle Reaches of the Yellow River, the Southwest and Northwest Economic Zone. The dense population and high level of economic development in the Southern Coastal and the Middle Reaches of the Yellow River, and the large proportion of raw coal consumption in the Southwest and Northwest Economic Zone may be the reasons for the relatively significant spatial agglomeration characteristics of pollutants and carbon dioxide emissions.

Since the provinces do not significantly show the regional distribution characteristics of the synergistic effect, this paper provides a more nuanced and rational segmentation for analysis.

Table 6 reveals that the coupling coordination degrees across the eight economic zones exhibit varying degrees of increase. Within this time frame, the southern coastal and northwest economic zones have consistently outperformed others. Guangdong Province, acknowledged as a pioneer in China's low-carbon initiatives and one of the seven pilot regions for carbon emission trading, has been at the forefront of climate change mitigation efforts. From the 12th to the 13th Five-Year Plan, Guangdong has notably advanced its environmental agenda, particularly post the latter plan. From 2011 to 2018, the province implemented a series of greenhouse gas control plans and programs, including Ecological Construction Emission Reduction and the Implementation Plan for Controlling Greenhouse Gas Emissions. These efforts actively explored a low-carbon development system and succeeded in surpassing the state-mandated target for reducing carbon dioxide emissions per unit of GDP. The northwest economic zone, characterized by its large area and sparse population, is located inland and far from major industrial hubs, resulting in relatively low pollutant emissions. Additionally, it boasts rich wind resources and ample sunlight. Among the nine large clean energy bases in China, four are situated in the northwest economic zone, facilitating emission reduction. Between 2012 and 2021, both the Northern Coastal and the Middle Reaches of the Yellow River Economic Zone advanced from a status of extreme dissonance to intermediate and good coordination. This improvement can be attributed to initiatives like the 12th Five-Year Plan for Air Pollution Prevention and Control in Key Regions, released in 2012, which targeted areas including Shanxi, Tianjin, Hebei, and Beijing. Policies within this plan imposed stringent regulations on projects with high energy use and significant pollution, implemented special emission limits, promoted the elimination of outdated production capacities, optimized industrial layouts, enhanced clean energy utilization, and regulated total coal consumption in these regions. For the Economic Zone in the Middle Reaches of the Yellow River, a notice from the General Office of the State Council in 2012, emphasized strengthening soil and water conservation efforts. Furthermore, in 2013, the Comprehensive Plan for the Yellow River Basin, which included adjustments to the energy structure, acceleration of industrial transformation, and enhancement of farmland soil carbon storage potential. For example, in 2014, the Shaanxi Provincial People's Government introduced a comprehensive five-year action plan aimed at pollution control and the enhancement of air quality. The synergistic effect in the Northeast, Middle Reaches of the Yangtze River, Southwest and Eastern Coastal Economic Zone are at a medium level, with slow growth in their coupling coordination degree. The Eastern Coastal Zone serves as a crucial platform for China's economic development, featuring a well-established industrial system and higher industrial standards. In its industrial restructuring process, these regions prioritize the development of low-carbon and green industries while actively phasing out backward production capacities that are high in pollution and energy consumption. Such actions contribute to reduced air pollutant emissions and improved air quality.The northeast economic zone, encompassing important industrial and agricultural bases, features a comprehensive industrial system. To achieve green development, various industries need to coordinate effectively to form a sustainable industrial chain. For instance, in equipment manufacturing, optimizing product design and improving energy efficiency can help accelerate the transition to a greener industrial chain, enhancing the coupling and coordination degree between the reduction of pollution and carbon. Concurrently, the economic zones in the Middle

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Reaches of the Yangtze River and the southwest are predominantly characterized by their tourism, and high-tech industrial sectors, with minimal heavy chemical industry presence. This composition substantially curtails air pollutant emissions. Furthermore, these economic zones are enriched with natural beauty and historical heritage, attracting numerous tourists and fostering a well-developed tertiary sector. The middle reaches of the Yangtze River economic zone benefits from a humid climate and fertile soil, conducive to crop cultivation. Recent investments by local governments in agriculture and the promotion of green agricultural technologies have further strengthened the synergistic effect.

Overall, the synergistic effect of reduction of pollution and carbon across the eight economic zones has improved to varying extents. This progress suggests that the issuance of relevant policy documents, enhancements in industrial structure, increased investment in environmental governance and technology research and development, as well as the application of energy-efficient and emission-abatement technologies has proven effective in fostering a synergistic decrease in pollutants and carbon dioxide.

3.4 GTWR Model Analysis of Spatial Effects of Influencing Factors

Ordinary Least Squares (OLS) regression can elucidate the influence of explanatory variables on dependent variables and facilitate predictions. The coefficient of each explanatory variable reflects both the strength and type of relationship with the dependent variable. A negative coefficient indicates an inverse relationship with the dependent variable, while a positive coefficient signifies a direct relationship. The results of OLS model test (Table 7) on the influencing factors of synergistic effect of reduction of pollution and carbon show that for the core explanatory variables, the OLS model is significant at the 1% level. Energy consumption total is the main influencing factor of the synergistic effect, and it has a negative impact, indicating that by optimizing the structure of energy consumption, developing new types of energy, improving energy utilization efficiency, and controlling fossil energy consumption, the synergistic effect between reduction of pollution and carbon can be greatly improved to a large extent. For the control variables, the results of OLS model test show that the three factors of urbanization rate, per capita GDP, and total import and export trade are significant at the 1% level, both the regional industrial structure and energy consumption structure were both determined to be significant at the 5% level. An escalation in the urbanization rate signifies a progressive augmentation of the secondary and tertiary sectors' share within the national economy, thereby leading to an optimization of the industrial structure. The third industry has been characterized by its low pollution and energy consumption, which is beneficial to reducing pollutant emissions and carbon emissions. The upgrading and transformation of the second industry is conducive to reducing pollutant emissions. As per capita GDP and living standards rise, there is a corresponding growth in energy demand. This surge, particularly in the consumption of fossil fuels, consequently results in heightened emissions of pollutants. An increase in total import and export trade is associated with a larger scale of trade development, and this expansion can lead to spatial agglomeration effects, with higher resource utilization efficiency and lower carbon emissions. These factors influence the synergistic effect indirectly through their impact on total energy consumption. The increase in the proportion of industrial added value in GDP indicates that the pace of industrial development is accelerating and enterprise profits are increasing, which will provide enterprises with more R&D investment and promote the research and application of clean production technology, thereby reducing pollutant and carbon emissions; The predominant share of fossil fuels in China's energy consumption structure is a primary contributor to elevated carbon emissions, so enhancing the proportion of clean and renewable energy sources is instrumental in advancing the synergistic effect.

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Table 7. Regression results of multicollinearity tests and OLS models

Explaining variable	VIF	OLS
Total energy consumption	3.12	-0.055*** (0.001)
Energy consumption structure	2.26	0.124** (0.037)
District industrial structure	2.16	0.397** (0.023)
Urbanization rate	5.32	1.256*** (0.000)
Per capital GDP	6.35	-0.316*** (0.000)
Total volume of import and export trade	2.47	0.037*** (0.000)

Note: ***, ** and * indicate the significance test at the levels of 1%, 5% and 10%, respectively.

Table 8. Moran's I test of coupling coordination degree and total energy consumption

Year	Coupling coordination degree	Total energy consumption
2012	0.368*** (0.000)	0.289*** (0.002)
2013	0.357*** (0.000)	0.234*** (0.006)
2014	0.356*** (0.000)	0.228*** (0.007)
2015	0.335*** (0.000)	0.213*** (0.010)
2016	0.235*** (0.005)	0.233*** (0.006)
2017	0.158** (0.031)	0.189** (0.020)
2018	0.054 (0.104)	0.130* (0.052)
2019	0.109* (0.056)	0.136* (0.053)
2020	0.087** (0.040)	0.191** (0.016)
2021	0.158** (0.019)	0.189** (0.019)

Note: ***, ** and * indicate the significance test at the levels of 1%, 5% and 10%, respectively

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The research on spatial auto-correlation aims to determine whether there is a spatial correlation between the attribute values of the studied sample points and those of other sample points in the field, and quantitatively describe the degree of spatial correlation among the samples. In order to analyze the spatial agglomeration effect of synergistic effect of reduction of pollution and carbon in China, this study examines the spatial agglomeration effect and total energy consumption in each province during that period. The results are presented in Table 8. Moran's I for coupling coordination degree and total energy consumption from 2012 to 2021 shows a positive value, indicating a positive spatial correlation. The global Moran index test confirms that both pollution reduction-coupling coordination degree and total energy consumption exhibit significant spatial aggregation from 2012 to 2017 as well as from 2019 to 2021. Moreover, total energy consumption also demonstrates significant spatial aggregation throughout the entire study period (from 2012 to 2021). Over time, Moran's I index varies, showing a declining trend in terms of the spatial aggregation characteristics observed for both pollution reduction-coupling coordination degree and carbon reduction as well as total energy consumption across different provinces.

Consequently, this paper identifies total energy consumption, energy consumption structure, regional industrial structure, urbanization rate, per capita GDP, and total import and export trade as influencing factors of the synergistic effect between reduction of pollution and carbon. Total energy consumption is designated as the core explanatory variable, with the others serving as control variables.

3.5 Regional Heterogeneity Analysis of Factors Affecting Carbon Emissions

Table 9 and Table 10 show the changes in spatial heterogeneity of total energy consumption from 2012 to 2020. The total energy consumption is the core explanatory variable for the synergistic effect of reducing pollution and carbon emissions. The variable has a negative impact on the synergistic effect. In 2012, the impact was stronger in areas such as northeastern, eastern coastal, and northern coastal economic zones, and in provinces like Ningxia, Shandong, Jiangsu, Shanghai, Henan, Anhui, Jilin, Liaoning, Shanxi, and Zhejiang. In 2021, the impact was stronger in northern coastal, Yellow River middle reaches, and northeastern economic zones, and in provinces such as Inner Mongolia, Hebei, Shanxi, Henan, Beijing, and Tianjin. The impact of total energy consumption on the synergistic effect within the eastern coastal economic zone has diminished, attributes to the reduction of standard coal consumption in Shanghai and Zhejiang, with a decrease of 549.98 million tons and 253.32 million tons from 2012 to 2021. For the control variables, the energy consumption structure has a negative impact on the synergistic effect in general, with a weak positive impact in a few provinces and increasingly stronger impact with stronger spatial differences. This is mainly because China has a huge energy consumption, with the energy structure dominated by fossil fuels and low clean energy share, which limits the synergistic effect. In 2012, the positive impact was mainly found in the Yellow River middle reaches, northern coastal, northwestern economic zones, and some provinces such as Sichuan, Fujian, and Qinghai. In 2021, the eastern coastal, southern coastal, and mid-Yangtze River economic zones exhibited the most significant positive impacts. The eastern coastal zone, being China's most economically advanced region, has extensively integrated new energy sectors and energy-efficient, eco-friendly technologies. This integration has progressively enhanced the visibility of the synergies between pollution reduction and carbon mitigation. The southern coastal region has relied on its abundant wind and solar energy and other clean energy resources to promote the transformation of energy consumption structure. Policy-driven initiatives have bolstered the deployment and exploitation of clean energy in the Yangtze River's midstream economic zone, thereby amplifying positive environmental impacts. Contrarily, the regional industrial structure's influence on pollution and carbon reduction synergies is predominantly negative, with notable concentrations in the Northeast and Southwest economic zones. This is exemplified by Shaanxi Province, historically a significant coal extraction and processing hub, where the industrial structure's negative impact was pronounced in 2012. Economic growth, as evidenced by increased industrial value in Gansu and Jilin, has spurred urban economic development and population influx. This demographic shift has escalated energy consumption in sectors such as urban transport and

Volume 11 Issue 1, 2025
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residential life, exacerbating air pollution. Concurrently, the urbanization rate's synergistic effect is primarily observed in the northern coastal economic zone and regions like the Yangtze River's midstream, Beijing, Hebei, Shanxi, Inner Mongolia, and Hunan. The influx of people to the eastern coastal economic zone, driven by economic development, has increased energy consumption, particularly in developing nations. To accommodate population growth, the exploitation of fossil fuels ensues, adversely affecting the synergies between pollution reduction and carbon mitigation. The per capita GDP's synergistic effect generally exerts a strong negative impact, particularly in the northern coastal regions and the Yellow River's midstream economic zone. Resource development often coincides with environmental pollution and ecological damage, and as economic development progresses, so does the severity of pollution issues. In regions like Inner Mongolia, industrial restructuring has been sluggish, with high-pollution, high-energy-consuming enterprises still holding significant positions, thus impeding the enhancement of pollution and carbon reduction synergies. Meanwhile, the total import and export trade's synergistic effect is generally positive but weak, with the main areas shifting from the Northwest and Southwest to the northwest, Yellow River's midstream, and the Northern Coastal Economic Zones. The Northwest Economic Zone, with lower economic development compared to the eastern coastal regions, hosts industries with lower carbon dioxide and pollutant emissions.

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Table 9. Regression coefficient of coupling coordination degree of pollution reduction and carbon reduction in 2012

Item	Regression coefficient	Spatial distribution
Total energy consumption	-1.2803~-0.9970	Ningxia, Shandong, Jiangsu, Shanghai, Henan, Anhui
	-0.9969~-0.7712	Jilin, Liaoning, Tianjin, Shaanxi, Zhejiang
	-0.7711~-0.6157	Hebei, Fujian, Hubei
	-0.6156~-0.4629	Beijing, Hunan, Jiangxi, Guangdong, Gansu, Qinghai, Xinjiang, Inner Mongolia, Shanxi, Heilongjiang
	-0.4628~-0.1856	Sichuan, Chongqing, Guizhou, Yunnan, Guangxi, Hainan
Energy consumption structure	-1.0743~-0.6399	Shandong, Henan, Anhui, Hubei
	-0.6398~-0.1768	Heilongjiang, Jilin, Liaoning, Jiangsu, Jiangxi
	-0.1767~0.0153	Xinjiang, Shaanxi, Chongqing, Yunnan, Guizhou, Hunan, Guangdong, Guangxi, Hainan, Zhejiang, Shanghai
	0.0154~0.2709	Gansu, Qinghai, Ningxia, Sichuan, Fujian, Tianjin
	0.2710~1.3876	Inner Mongolia, Shanxi, Hebei, Beijing
District industrial structure	-0.4987	Shaanxi
	-0.4986~-0.1843	Jilin, Liaoning, Gansu, Chongqing, Guizhou, Yunnan, Guangxi
	-0.1842~-0.0907	Xinjiang, Qinghai, Sichuan, Tianjin, Shandong, Henan, Hunan, Guangdong, Hainan
	-0.0906~0.0536	Heilongjiang, Hebei, Jiangsu, Shanghai, Anhui, Zhejiang, Fujian, Jiangxi, Hubei
	0.0537~0.1587	Beijing, Shanxi, Ningxia, Inner Mongolia
Urbanization rate	-0.6139~-0.1218	Shaanxi, Henan, Shandong, Jiangsu, Anhui, Shanghai, Zhejiang
	-0.1217~0.1646	Heilongjiang, Fujian, Gansu, Qinghai
	0.1647~0.3157	Xinjiang, Jilin, Sichuan, Chongqing, Guizhou, Yunnan, Guangdong, Guangxi, Hainan
	0.3158~0.4570	Ningxia, Liaoning, Tianjin, Hubei, Jiangxi
	0.4571~0.9746	Beijing, Hebei, Shanxi, Inner Mongolia, Hunan
Per capital GDP	-2.0527~-1.3611	Inner Mongolia, Beijing, Hebei, Shanxi, Ningxia
	-1.3610~-0.4384	Tianjin, Liaoning, Qinghai, Sichuan, Hunan, Jiangxi
	-0.4383~0.2834	Xinjiang, Gansu, Heilongjiang, Jilin, Hubei, Chongqing, Guizhou, Fujian, Guangdong, Guangxi, Yunnan, Hainan
	0.2835~1.2886	Shaanxi, Shandong, Jiangsu, Anhui, Shanghai, Zhejiang
	1.2887~2.4119	Henan
Total volume of import and export trade	-1.6882~-1.0034	Shanghai, Jiangsu, Zhejiang, Anhui, Hubei
	-1.0033~-0.3110	Beijing, Tianjin, Liaoning, Inner Mongolia, Shanxi, Hebei, Shandong
	-0.3109~-0.0250	Jilin, Shaanxi, Henan, Hainan, Guangdong, Guangxi, Guizhou, Hunan, Jiangxi, Fujian
	-0.0249~0.6927	Xinjiang, Qinghai, Sichuan, Chongqing
	0.6928~5.8251	Heilongjiang, Ningxia, Gansu, Yunnan

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Table 10. Regression coefficient of coupling coordination degree of pollution reduction and carbon reduction in 2021

Item	Regression coefficient	Spatial distribution
Total energy consumption	-0.9310~-0.8429	Inner Mongolia, Hebei, Shanxi, Shandong, Henan, Beijing, Tianjin
	-0.8428~-0.6720	Ningxia, Shaanxi
	-0.6719~-0.3862	Xinjiang, Sichuan, Jilin, Liaoning, Jiangxi, Fujian
	-0.3861~-0.2624	Gansu, Qinghai, Shanghai, Jiangsu, Zhejiang, Anhui, Hubei, Chongqing, Hunan, Guizhou, Yunnan, Guangxi, Hainan
	-0.2623~-0.1502	Heilongjiang, Guangdong
Energy consumption structure	-0.3429~-0.3295	Inner Mongolia, Shanxi
	-0.3294~-0.0644	Xinjiang, Jilin, Beijing, Hebei, Shaanxi
	-0.0643~0.0488	Liaoning, Gansu, Qinghai, Ningxia, Henan, Chongqing, Yunnan, Guizhou, Guangxi, Hainan
	0.0489~0.1120	Tianjin, Heilongjiang, Sichuan, Hunan, Jiangxi, Fujian, Guangdong
	0.1121~0.1772	Jiangsu, Zhejiang, Shandong, Anhui, Hubei, Shanghai
District industrial structure	-0.1725~-0.1372	Xinjiang, Hunan
	-0.1371~-0.0452	Heilongjiang, Jilin, Gansu, Qinghai, Hubei, Shanghai, Zhejiang, Jiangxi, Fujian, Guangdong, Hainan
	-0.0451~-0.0028	Jiangsu, Anhui, Sichuan, Chongqing, Guizhou, Guangxi, Yunnan
	-0.0027~0.0688	Liaoning, Ningxia
	0.0689~0.2114	Inner Mongolia, Beijing, Tianjin, Hebei, Shanxi, Shaanxi, Shandong, Henan
Urbanization rate	-0.1531~-0.1003	Jiangsu, Shanghai, Zhejiang, Fujian, Anhui, Jiangxi, Hubei
	-0.1002~-0.0232	Inner Mongolia, Jilin, Liaoning, Beijing, Hebei, Shanxi, Shaanxi, Guangdong
	-0.0231~0.0367	Tianjin, Shandong, Henan, Ningxia, Gansu, Qinghai, Sichuan
	0.0368~0.1037	Heilongjiang, Chongqing, Hunan, Guizhou, Guangxi, Yunnan
	0.1038~0.3483	Xinjiang
Per capital GDP	-0.4815~-0.3351	Tianjin, Shandong, Henan
	-0.3350~-0.1105	Beijing, Hebei, Shaanxi
	-0.0104~0.0313	Xinjiang, Inner Mongolia, Shanxi, Sichuan, Chongqing, Yunnan, Guizhou, Hunan
	0.0314~0.1269	Ningxia, Gansu, Qinghai, Liaoning, Hubei, Jiangxi, Fujian, Guangdong, Guangxi, Hainan
	0.1270~0.4123	Heilongjiang, Jilin, Jiangsu, Shanghai, Zhejiang, Anhui
Total volume of import and export trade	-1.9687	Heilongjiang
	-1.9686~-0.0905	Jilin, Shanghai, Jiangsu, Zhejiang, Anhui, Hubei
	-0.0904~0.0312	Liaoning, Gansu, Qinghai, Chongqing, Yunnan, Guizhou, Hunan, Jiangxi, Fujian, Guangdong, Guangxi, Hainan
	0.0313~0.6151	Xinjiang, Ningxia, Shandong, Henan, Sichuan
	0.6152~1.2505	Inner Mongolia, Beijing, Tianjin, Hebei, Shanxi, Shaanxi

4. Conclusion and Suggestions

4.1 Conclusion

From the perspective of total energy consumption, this paper calculates the emission of pollutants and carbon dioxide, and analyzes the changes of the synergistic effect between reduction of pollution and carbon in China at the national level, provincial level and eight Economic Zones from 2012 to 2021. The GTWR model is used to study the possible influencing factors of the synergistic effect between reduction of pollution and carbon in the whole country, all provinces, eight regions. The following basic conclusions are drawn:

In terms of the time series of pollutants and carbon dioxide emissions, From 2012 to 2021, carbon dioxide emissions declined slowly with time, with the highest value being 3.020 billion tons in 2012 and the lowest value being 2.329 billion tons in 2021, with a decrease of 29.64%. Pollutant emission equivalent has decreased significantly since 2014, with the highest value being 39.777million tons in 2014 and the lowest value being 7.582million tons in 2021, indicating a significant decrease in emission equivalent.From a provincial perspective, the equivalent emissions of carbon dioxide and industrial waste gases are predominantly concentrated in Shandong, Hebei, Shanxi, Inner Mongolia, Liaoning, Jiangsu Province, and several other provinces. When considering the eight economic zones, carbon dioxide emissions and pollutant emission equivalents are primarily concentrated in the middle reaches of the Yellow River, the northeastern, the northern coastal economic zone.

In terms of the synergistic effect between reduction of pollution and carbon, spatial differentiation at the provincial level indicates that the synergistic effect across 30 provinces in China demonstrated an overall upward trend from 2012 to 2021. This trend can be categorized into three stages: 2012−2014, 2015−2017, and 2018−2021. The number of provinces exhibiting good coordination and quality coordination has gradually increased, now accounting for two-thirds or more of the total number of provinces. At the level of the eight economic zones, the coupling and coordination levels have improved to varying degrees. During the study period, the coupling and coordination levels in the Northwest and the Southern Coastal Economic Zone were higher than others. The middle reaches of the Yellow River and the Northern Coastal Economic Zone have progressed from a severely unbalanced state to intermediate coordination, and subsequently to a well-coordinated state.

In terms of the influencing factors of the synergistic effect between reduction of pollution and carbon, total energy consumption is the core influencing factor, and there is an obvious negative correlation. For the control variables, China can promote the realization of the synergistic effect by improving the regional industrial structure, enhancing the economic level and the level of opening up to the world, which requires each region to combine its own advantages, take measures according to local conditions, and effectively use the positive driving or negative hindering effect of each factor.

4.2 Suggestions

To enhance the achievement of synergistic effects between pollution reduction and carbon mitigation in China, drawing from the aforementioned findings, this study proposes the subsequent strategies and recommendations aimed at facilitating the attainment of China's carbon peak and neutrality objectives:

We will accelerate the transformation of clean and low-carbon energy consumption in the industrial sector. Total energy consumption is the most important factor affecting the synergistic effect between reduction of pollution and carbon, and it impedes the attainment of this synergistic effect in all provinces. Hastening the achievement of carbon peak and neutrality goals, it is imperative to foster intensive and sustainable industrial development, with a particular focus on the heavy chemical sector. To achieve clean and low-carbon development of energy consumption, there is a need to expedite innovation and application of energy-saving technology and equipment in key energy-using industries or energy-intensive industries. Power grid construction can also be carried out in industrial parks, and measures such as rooftop photovoltaics can be taken to realize the conversion and utilization of various energy sources. Offshore wind power should be reasonably constructed in coastal areas; We will actively develop wind power in the relatively vast and flat areas, such as the northwest economic zone, and develop photovoltaic and other renewable energy in the areas with long sunshine hours and sufficient sunshine; The Southwest Economic Zone should promote the comprehensive utilization of water, wind and solar energy as a whole. By developing clean energy and improving energy efficiency, total energy consumption can be reduced, to enhance the synergistic effect between reduction of pollution and carbon.

We will strengthen scientific and technological support for promoting the synergistic effect between reduction of pollution and carbon. The transformation of clean and low-carbon energy consumption needs to be driven by technological progress. China has a large population, a heavy industrial structure, and urbanization is still in the process of advancing. On the premise of ensuring the demand for energy consumption, promoting clean and low-carbon energy consumption needs to be realized through scientific and technological innovation. In provinces with better economic development, on the premise that technological R&D and innovation have the economic guarantee, innovative carbon capture, utilization and storage technologies can be developed and applied, or low-cost, high-benefit and deep decarbonization technologies and low-carbon, zero-carbon and negation-carbon technologies with obvious emission reduction effects can be actively developed to effectively reduce carbon dioxide emissions. In the provinces with relatively unsatisfactory economic development level but the vast territory, the key technologies of solar energy, wind energy and other energy sources can be used. With the backing of national policies, a power system primarily based on renewable energy can be established, reducing the generation costs below those of coal-fired power plants. Based on China's reality, the shift towards clean and low-carbon energy consumption, facilitated by technological innovation, can propel the country onto a path of sustainable and eco-friendly development.

We will strengthen regional cooperation and achieve coordinated governance among regions. The interaction between the state and relevant institutions in different provinces and regions, the design of pollution reduction and carbon reduction synergy principles and policies in key industries according to local conditions, and the joint development of trans-regional collaborative governance plans in similar regions. It can be modeled on China's "South-to-north water diversion" projects to transport electricity generated in areas rich in clean energy, such as biomass, electricity, nuclear energy and tidal energy, to areas that are unsuitable for the advancement of clean energy. At the same time, inter-regional cooperation should be strengthened, so that the places with poor synergistic effect can learn from the policies of neighboring areas with good synergistic effect between reduction of pollution and carbon because of the relative disparities in geographical positioning and economic development between neighboring regions. At the same time, combined with the industrial structure and development status of each region, we should encourage the technology and industry transfer from the more developed regions to the less developed regions, realize the optimization of industrial layout among regions and collaboratively advance the synergies between pollution reduction and carbon mitigation to enhance the nation's economic productivity and environmental sustainability.

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