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Original Research

The Impact of Low-Carbon Pilot Policy on Carbon Emissions: Evidence from 212 Chinese Cities

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Abstract

Reducing urban carbon emissions efficiently achieves green, low-carbon, and sustainable development goals and mitigates climate change. This paper aims to assess the impact and mechanism of China's innovative low-carbon pilot policy on carbon emissions. Based on a sample of 212 cities in China from 2003 to 2016, this paper investigates the impact of low-carbon pilot policy on urban carbon emissions using the DID technique. The findings reveal that pilot cities cut carbon emissions considerably by roughly 24.5% compared to non-pilot cities when the policy is implemented. This reduction remains significant after several robustness tests. Additionally, the low-carbon pilot policy reduces urban carbon emissions primarily through investments in technological innovation, energy conservation, carbon sinks, and environmental governance. In contrast, the impact of industrial restructuring on reducing urban carbon emissions is currently insignificant. Regarding differences between regions, the east region and high-quality cities have a greater impact on reducing carbon emissions. In addition to helping China reach its "peak carbon" and "carbon neutral" objectives, low-carbon pilot initiatives have served as a model for other nations and regions looking for ways to reduce their carbon emissions.

Keywords: low-carbon pilot policy, carbon emissions, difference-in-differences model, China

Introduction

In response to climate change and the need for economic transformation, major economies worldwide have proposed low-carbon development goals [1–6]. China proposes to "peak carbon emissions in 2030 and achieve carbon neutrality in 2060" (the dual-carbon goal) and stresses the need to "accelerate the green economy transition" [7, 8]. To achieve low-carbon and sustainable development goals, China has actively participated in climate change governance by drawing up three batches of low-carbon pilot cities in 2010, 2012, and 2017, respectively. The policy aims to comprehensively promote low-carbon urban development, improve air quality, and achieve sustainable and green economic development by improving energy utilization efficiency, promoting the low-carbon

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transformation of high-carbon industries, and optimizing energy structure and resource allocation [9–11].

Cities are China's primary carbon emissions source, accounting for approximately 85% of total carbon emissions in China [12]. Studying the impact of low-carbon pilot policy on urban carbon emissions is strategically important for achieving the dual-carbon goal. Analyzing the impact mechanisms and regional differences can also provide a reference for non-pilot cities to reduce carbon emissions. Current research on low-carbon pilot policy focuses on the following three areas. The first aspect focuses on environmental governance, mainly assessing whether the policy implementation achieves the desired effect [13–15] and has a spillover effect on non-pilot cities [16]. The second aspect focuses on firms, mainly evaluating the impact of the policy on firms' green technological innovation [17–19] and production efficiency promotion [20]. The third area focuses on industry, mainly studying the effects of low-carbon pilot policy on reducing industrial carbon emissions [21], adjusting industrial structure [22, 23] and improving energy efficiency [24].

In summary, great literature studies the indirect effects of low-carbon pilot policy. Still, there is less literature assessing the direct effects of the policy on carbon emissions. Thus, this paper aims to empirically evaluate the impact and mechanism of low-carbon pilot policy on carbon emissions based on a sample of 212 cities in China from 2003 to 2016.

The marginal contributions of this paper include:

(1) We enrich the literature on assessing the impact of policies on carbon reduction by studying the impact of low-carbon pilot policy on carbon emissions at the urban level, thus obtaining more targeted results than national or regional level research;

(2) From the viewpoint of industrial restructuring, technological innovation, energy conservation, carbon sink and environmental governance investment, this paper probes into the impact mechanism of low-carbon pilot policy on carbon emissions, which diversifies and expands the literature on carbon reduction pathways;

(3) The existing studies usually classify sample cities according to population size, while this paper classifies cities from the perspective of the administrative level in China. This classification method considers the differences in urban population, resource endowment, and strategic status in cities, thus enriching and expanding the literature on the differences in policy carbon-reduction effects. This study provides possible empirical support for the effective promotion of carbon reduction experience in pilot cities.

This paper considers low-carbon pilot policy as a quasi-natural experiment and empirically investigates the impact of the policy on urban carbon emissions using the difference-in-differences model. The remainder of this paper is structured as follows.

Policy Background and Literature Review

Policy Background

The low-carbon pilot policy in China aims to develop a low-carbon economy and cultivate the low-carbon and green ways of living among residents. Since the policy was deployed in 2010, there have been 6 low-carbon pilot provinces and 36 low-carbon pilot cities. The low-carbon urban development is mainly achieved by popularizing the concept of a low-carbon economy, optimizing industrial structure, and improving energy efficiency. A low-carbon pilot policy in different provinces and cities is conducive to accumulating carbon reduction experience and effectively mitigating climate change. The government implements the concept of low-carbon administration. It drives enterprises and residents to pursue low-carbon production and life while actively participating in low-carbon urban construction. With the joint efforts of enterprises, residents, and the government, the low-carbon pilot policy can be realized to be of maximum effectiveness.

Regarding enterprise production and residents' livelihoods, low-carbon production and life are mainly achieved by adjusting the industrial structure, promoting technological innovation, and decreasing energy consumption. In terms of industrial structure adjustment, pilot cities guide the transformation of high-pollution and high-energy consumption industries to environment-friendly and resource-friendly industries, improve industrial production efficiency, and build a green and recyclable industrial system. In terms of technological innovation, pilot cities support enterprises in green technological innovation and strengthen environmental constraints to guide enterprises to take green production research and improve the low-carbon production capacity of enterprises. Regarding energy conservation, pilot cities increase the proportion of clean energy consumption and reduce coal usage to optimize the energy consumption structure and promote the energy efficiency of enterprise production and residents' livelihoods, building a low-carbon production and life system.

Regarding government administration, low-carbon administration is mainly achieved by increasing urban carbon sinks and environmental governance investment. In terms of increasing urban carbon sinks, the pilot cities enhance the capacity to absorb carbon dioxide and control carbon emissions by planting trees, greening wastelands, and increasing the greening coverage of built-up areas. In terms of environmental governance investment, the pilot cities increase environmental protection expenditures, improve urban public health service facilities, and regulate environmental pollution more strictly to implement low-carbon administrative goals.

Literature Review

To cope with climate change and improve the ecological environment, countries worldwide have adopted diverse environmental regulations. The practices of major global economies to reduce carbon emissions can be divided into establishing a carbon pricing mechanism and encouraging a green-oriented energy transition.

In evaluating the effects of carbon pricing mechanisms on carbon reduction, existing international studies focus on carbon emissions trading and taxes. Regarding carbon trading, Bayer et al. (2020) [25] assessed the carbon reduction effect of the EU ETS at a lower trading price. The system reduced about 1.2 billion tons of carbon emissions from 2008 to 2016. In terms of carbon tax, Murray et al. (2015) [26] conclude that British Columbia's carbon tax policy has reduced its GHG emissions by 5% to 15%; meanwhile, the study finds that the policy has had a minimal impact on the economy and received widespread public support after the policy was implemented for three years.

Regarding energy policy, Wakiyama et al. (2021) [27] measured panel data for 50 continents in the U.S. from 1990 to 2014 and used a recursive generalized linear model to investigate the impact of electricity market reforms and local climate policies on carbon emissions. The result shows that electricity market reforms reduce electricity consumption per unit of GDP, and the reduction in energy intensity and the increase in renewable energy usage jointly reduce carbon emissions. Fuinhas et al. (2017) [28] assesses the impact of renewable energy policy on carbon emissions of 10 countries in Latin America from 1991 to 2012 using a panel autoregressive distributional lag approach and shows that there is a positive relationship between per capita energy consumption and carbon emissions. Renewable energy policy reduces per capita carbon emissions.

Since the establishment of the first pilot cities in China, research on low-carbon pilot policy has gradually covered more areas, mainly focusing on the direct effects of low-carbon pilot policy on environmental issues such as carbon emissions and the indirect effects of low-carbon pilot policy on other aspects.

In terms of direct impacts, existing studies differ in research methods and impact mechanisms. In terms of research methods, Wang et al. (2019) [29] use kernel density estimation, spatial autocorrelation, spatial Markov chain, and panel quantile regression to regress panel data of 283 cities across China from 1992 to 2013 to estimate the spatial spillover effect of urban carbon emission intensity. The results show that the mean value of urban carbon emission intensity decreases and has a significant spatial agglomeration effect. Using the Super-SBM model with non-expected output, Xu et al. (2022) [30] measure the spatial and temporal evolution characteristics of carbon emission efficiency in 68 low-carbon pilot cities across China and find that the carbon emission efficiency of low-carbon cities generally improves but with regional differences. In terms of impact mechanisms, Zhou et al. (2019) [31] find that low-carbon pilot cities mainly reduce carbon emissions by improving energy efficiency and optimizing industrial structure. Based on the relationship between local economic structure, development level, and carbon emissions, Yu et al. (2020) [32] classify pilot cities into low-carbon mature, low-carbon growth, and low-carbon post-hair and propose to select differentiated carbon reduction paths according to local characteristics of pilot cities.

In terms of indirect policy impacts, Xu et al. (2020) [33] studied the impact of low-carbon pilot policy on corporate green technological innovation based on green patent application data of A-share listed companies in Shanghai and Shenzhen markets from 2005 to 2015 using a difference-in-differences model. The results show that low-carbon pilot policy significantly affects green technological innovation in high-carbon industries and non-state-owned enterprises. Zhang et al. (2021) [34] studied the impact of low-carbon pilot policy on total factor energy efficiency in cities. The results show that low-carbon pilot policy significantly improves total factor energy efficiency in cities. Different policy instruments improve total factor energy efficiency in different ways. Wang et al. (2022) [35] concluded that the low-carbon pilot policy dramatically increased the employment rate of enterprises through the output effect and factor substitution effect.

The existing studies are rich in research methods and indirect effects of low-carbon policies, which lay the foundation for further research in this paper. However, the impact mechanisms of the low-carbon pilot policy need to be further explored, and the different impacts of the policy in different regions need to be further analyzed based on the development differences of cities. This paper investigates the impact mechanisms of the policy from a more detailed perspective based on the difference-in-differences (DID) model and analyzes the differences in the effects of carbon emission reduction from regional and administrative hierarchy differences.

Materials and Methods

Model Specification and Description

This paper mainly studies whether a low-carbon pilot policy in China can effectively reduce urban carbon emissions. To find the endogenous problem, this paper adopts the DID model and removes the effects of time effects and other unobservable factors. The DID model can investigate the net effect of policy implementation by differing whether the experimental group and the control group are affected by the policy or not and the experimental group before and after the policy implementation [36]. The cities included in the low-carbon pilot are set as the experimental group, and those not in the low-carbon pilot are set as the control group. Suppose there is no difference in carbon emissions between the experimental group and the control group before being affected by the policy. In that case, it is considered that the low-carbon pilot policy brings the carbon reduction effect of the experimental group. The specific model is set as follows:

$$CO_{2it} = \alpha + \beta \times Treat_{it} + Control_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (1)$$

Where CO_{2it} denotes the carbon emissions of the city i in year t; $Treat_{it}$ denotes whether city i has implemented the low-carbon pilot policy in year t. If city i has implemented the low-carbon pilot policy in year t, the value is assigned to 1, and vice versa. If city i has not implemented the low-carbon pilot policy in year t, the value is assigned to 0; $Control_{it}$ denotes a set of control variables that affect city i in year t; μ_i and ν_t denote city-fixed effects and year-fixed effects, respectively; ε_{it} denotes the random perturbation term; β is the coefficient focused on in this paper, representing the impact of low-carbon pilot policy on urban carbon emissions, and if $\beta < 0$, it means that low-carbon pilot policy reduces city carbon emissions.

Variable selections

Explained variables. The explained variable in this paper is urban carbon emissions, represented by the logarithmic of urban carbon emission data. in formula (1). The data are obtained from the China Carbon Accounting Database (CEADs), and several missing values are interpolated to complete the data.

Core explanatory variables. The core explanatory variable in this paper is the low-carbon city pilot policy, denoted by Treat. According to the "Circular on Pilot Work on Low Carbon Provinces and Low Carbon Cities," "Circular of the National Development and Reform Commission on Pilot Work on the Second Batch of Low Carbon Provinces and Low Carbon Cities," and "Circular of the National Development and Reform Commission on Pilot Work on Low Carbon Cities in the Third Batch of Countries," China conducts three batches of low-carbon pilot cities in 2010, 2012 and 2017 respectively. Due to the limited data, the first two batches of low-carbon pilot cities were selected for this paper.

Control variables. Due to certain variables at the city level may impact the dependent variable, some control variables are selected, which are expressed as follows:

Industrial structure: In this paper, the proportion of value added by secondary industry to GDP(PVASI) is selected as an indicator representing industrial structure. Since polluted industries mostly dominate the secondary industry, the more the city relies on the secondary industry for development, the higher its carbon emissions may be. This paper adds industrial structure as a control variable to exclude its interference.

Regional economic development level: In this paper, gross regional product (GDP) is selected as an indicator to measure the regional economic development level. Economic development characterized by industrialization and urbanization has rapidly increased energy consumption and carbon emissions [37]. Therefore, this paper chooses to introduce regional GDP as a control variable.

Energy consumption: In this paper, electricity consumption per unit of GDP (E.C.) is chosen as an indicator to measure the urban intensity of energy consumption. Higher electricity consumption per unit of GDP represents higher energy consumption intensity, possibly leading to higher carbon emissions. Therefore, it is selected as a control variable in this paper.

Population size: In this paper, the total population (Population) is selected as the indicator of population size. The scale effect brought by the increase in population size causes increased carbon emissions [37].

Scientific research investment: This paper selects scientific expenditure (SCIE) as an indicator to measure scientific research investment. Increasing scientific research investment may improve the urban green innovation level and thus suppress carbon emissions [38].

Mechanism variables. Based on the above policy interpretation, this paper adopts industrial structure, technological innovation, energy consumption, carbon sink, and environmental governance investment as the mechanism variables. In terms of industrial structure, this paper selects the proportion of value added by secondary industry to GDP(PVASI) and the proportion of value added by tertiary industry to GDP(PVATI) as indicators; in terms of technological innovation, this paper selects the total number of annual patents granted (PG) in cities as an indicator; in terms of energy consumption, this paper selects the urban annual electricity consumption (AEC) as an indicator; in terms of carbon sink, this paper selects the green area per capita (GA) as an indicator; in terms of environmental governance investment, this paper selects the investment in urban sanitation (SAN) as an indicator.

The city-level data are obtained from the "China City Statistical Yearbook," "China Statistical Yearbook," "China Electricity Yearbook," "China Regional Economic Statistical Yearbook," and the "Environmental Protection Bulletin" from each province and city. Due to the lack of data, the urban data of Tibet and Xinjiang provinces are excluded from this paper. 212 prefecture-level urban panel data from 2003 to 2016 are finally selected. The descriptive statistics of the above variables are presented in Table 1.

Results

DID Regression Results

The DID regression results are presented in Table 2. Column (1) shows the regression results without any control variables, while the remaining columns show the regression results with the control variables. The coefficients of core explanatory variables in each column are negative and statistically significant at the 5% level, which indicates that the low-carbon pilot policy significantly reduces urban carbon emissions. With the introduction of control variables, the carbon emissions of pilot cities significantly decreased by about 24.5% compared to non-pilot cities. In addition, the absolute values of coefficients of core explanatory variables increase as the control variables are introduced. This indicates that the net effect of a low-carbon pilot policy in reducing carbon emissions becomes more obvious after continuously reducing interference factors.

Robustness Test

Parallel Trend Test

Parallel trend assumption is an important prerequisite for using the DID method. This implies that the changes in urban carbon emissions between the experimental

Table 1. Descriptive statistics of the variables.

Variables	Sample size	Average value	Standard deviation	Minimum value	Maximum value
Carbon emissions	2,968	0.3685	0.3576	0.0004	3.0145
Treat	2,968	0.0515	0.2212	0.0000	1.0000
Population	2,968	0.1590	0.1955	0.0164	2.4490
GDP	2,968	0.1108	0.2328	0.0018	2.8000
AEC	2,968	0.9091	1.4251	0.0022	15.0000
EC	2,968	0.1251	0.0915	0.0164	0.9667
PG	2,968	0.3071	0.8046	0.0002	10.2205
SCIE	2,968	0.4687	2.1725	0.0000	40.0000
PVASI	2,968	0.5203	0.1167	0.1636	0.9097
PVATI	2,968	0.4219	0.1067	0.0858	0.7859
GA	2,968	0.3786	0.2451	0.0088	1.1998
SAN	2,968	0.9851	5.9089	0.0000	200.0000

Table 2. Impact of low-carbon Pilot Policy on urban carbon emissions.

Variables	Carbon emissions					
	(1)	(2)	(3)	(4)	(5)	(6)
Treat	-0.126**	-0.215**	-0.216**	-0.232**	-0.234**	-0.245**
	(0.063)	(0.103)	(0.102)	(0.103)	(0.103)	(0.101)
GDP	–	Yes	Yes	Yes	Yes	Yes
Population	–	–	Yes	Yes	Yes	Yes
PVASI	–	–	–	Yes	Yes	Yes
E.C.	–	–	–	–	Yes	Yes
SCIE	–	–	–	–	–	Yes
Urban fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Sample size	2968	2945	2945	2945	2945	2945
Adjusted R^2	0.664	0.618	0.618	0.622	0.623	0.628

Note: Robust standard errors at the city level are in parentheses; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

and control groups will converge before implementing the low-carbon pilot policy. This paper refers to the event analysis method proposed by Jacobson et al. (1993) [39] to conduct the parallel trend test, and the specific model is set as follows:

$$CO_{2it} = \alpha + \beta \times \Sigma_{t=-6}^{t=6} X_{it} + Control_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (2)$$

Where X_{it} It is a dummy variable for whether city i is affected by the policy in the year t. If city i has implemented the low-carbon pilot policy in year t, and the value is assigned to 1, otherwise the value is assigned to 0. The remaining variables represent the same meanings as in equation (1). The results of the parallel trend test are shown in Fig. 1.

From Fig. 1, the estimated coefficients of urban dummy variables of the experimental and control groups fluctuate around 0 before the implementation of the low-carbon pilot policy, and a value of 0 falls within confidence intervals, indicating that there is no significant difference between the experimental and control groups before the policy shocks. However, after the policy is implemented, the estimated

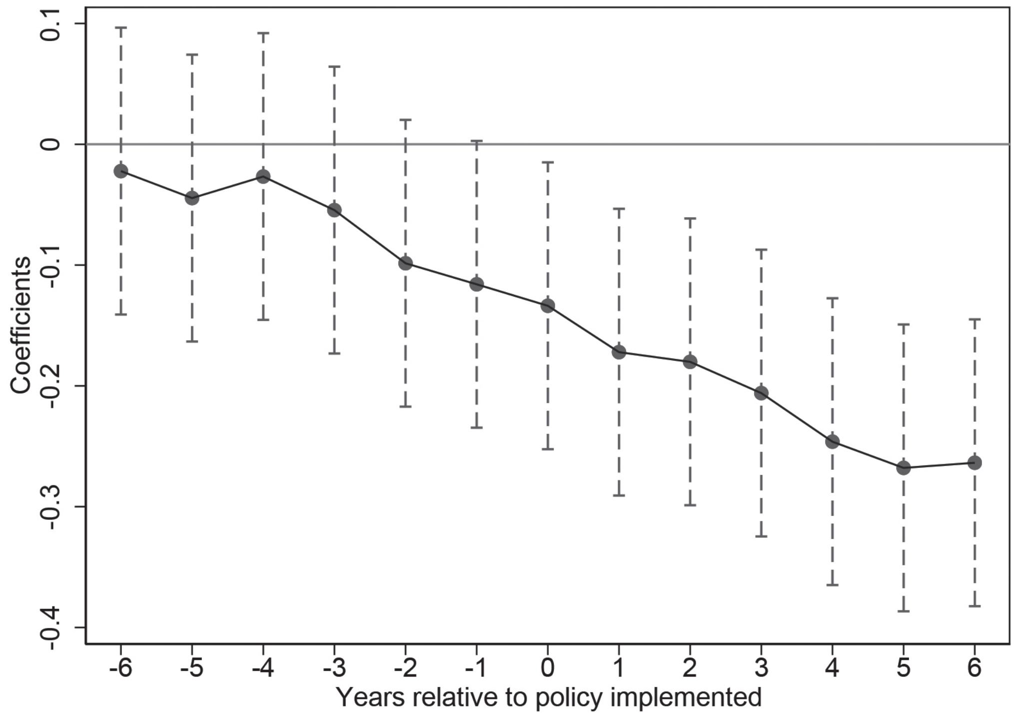

Fig. 1. Parallel trend test.

Note: The solid dots in the figure represent the coefficient β in Equation (2), and the short vertical dashed lines represent the upper and lower 95% confidence intervals corresponding to the coefficient β.

coefficients of dummy variables are significantly negative, indicating that the low-carbon pilot policy negatively affects urban carbon emissions. In summary, the parallel trend test passed.

Placebo Test

To exclude the effects of other unobservable factors, this paper draws on the method by Ferrara et al. (2012) [40] to conduct a placebo test by randomly selecting one year as the year when the low-carbon pilot policy is issued in the experimental group of cities, a set of dummy variables is reconstructed for regression. The process is repeated 500 times to obtain the placebo test results presented in Fig. 2.

As can be observed in Fig. 2, the estimated coefficients of the spurious dummy variables are normally distributed around 0. The p-value is greater than 0.1, and the regression results are insignificant. So, it is suggested that no other unobservable factors significantly affect the DID regression results, and the baseline results of this paper remain robust.

Propensity Score Matching

To mitigate the errors caused by non-random selection and minimize the systematic differences between the experimental and control groups, the nearest-neighbor matching method is chosen to re-match the data in this paper, and the DID method is used for regression. The results obtained are presented in Column (1) of Table 3. The table shows that the estimated coefficients are negative at a 10% significance level and are not significantly different from the DID regression results, which indicates that the baseline regression results are robust.

Removal of Sample Extremes

They eliminate the influence of extreme values in the sample on the DID regression results. This paper conducts the DID regression after the 1% tailing of the dependent variable, and the regression results are shown in Column (2) of Table 3. The coefficient estimates are significantly negative and similar to the estimated coefficients of DID regression, which verifies the conclusions of this paper.

Exclusion of Contemporaneous Interference Policy Impact

To exclude the influence of other policies on urban carbon emissions during the study period, this paper introduces contemporaneous competing policies, namely,

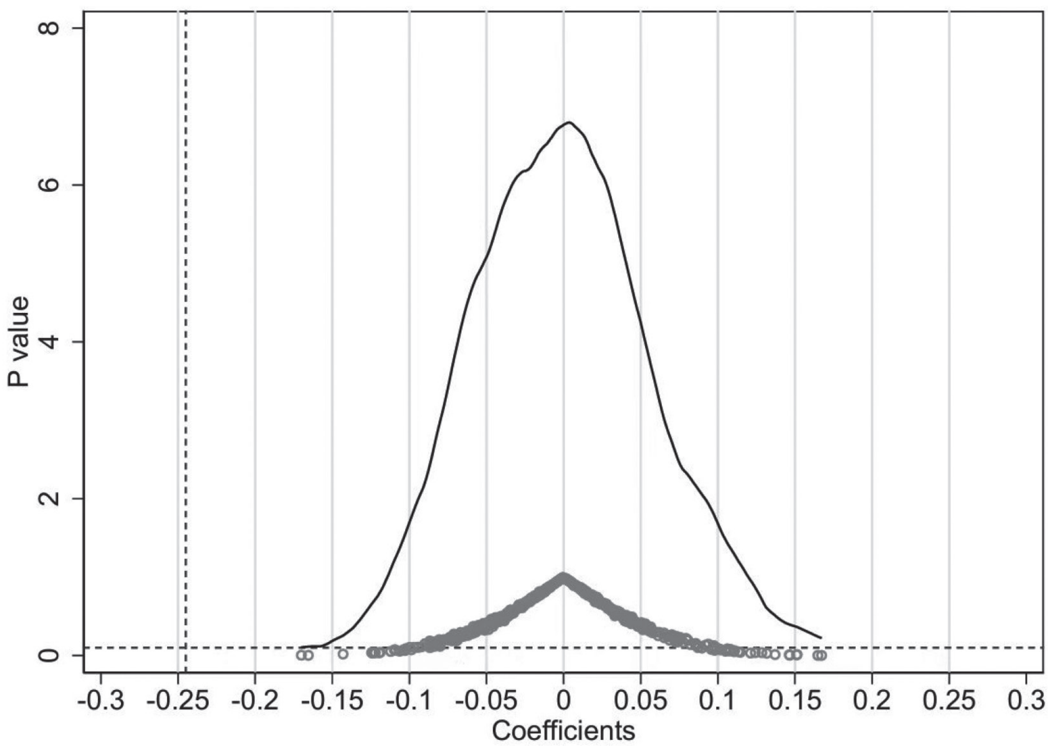

Fig. 2. Placebo test.

Table 3. Robustness Tests-Propensity Score Matching, Exclusion of Extreme Values, and Exclusion of Competitive Policy Interference.

Variables	PSM-DID	1% shrinkage	Competitive Policy		
			Smart City	Innovative Cities	Forest City
	(1)	(2)	(3)	(4)	(5)
Treat	-0.185* (0.100)	-0.235** (0.100)	-0.248** (0.101)	-0.250** (0.199)	-0.243** (0.199)
Control variables	Yes	Yes	Yes	Yes	Yes
Urban fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	2786	2945	2945	2945	2945
Adjusted R^2	0.643	0.642	0.629	0.630	0.628

smart city pilot policy, innovation city pilot policy, and forest city pilot policy. Adding these policies as dummy variables in the DID regression, the regression results are shown in Columns (3) to (5) of Table 3. As can be seen in the table, the coefficient estimates in DID regression are negative at the 5% significance level after the introduction of contemporary disturbance policies, respectively, indicating the regression results are robust.

Impact Mechanism Test

In its study of the impact mechanism of low-carbon pilot policy on urban carbon emissions, this article draws on the approach of Li et al. (2014) [41]. We first examine the impact of low-carbon pilot policy on urban industrial restructuring, technological innovation, energy conservation, carbon sinks, and environmental governance investments, respectively, and then investigate the impact of the interaction of the above five mechanism variables and low-carbon pilot policy on urban carbon emissions. The specific model is built as follows:

$$M_{it} = \alpha + \beta_1 \times Treat_{it} + Control_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (3)$$

$$CO_{2it} = \alpha + \beta_2 \times M_{it} \times Treat_{it} + Control_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (4)$$

Table 4. Impact of low-carbon pilot policy on carbon emissions through industrial restructuring.

Variables	Industrial Structure-Secondary Industry	Carbon emissions	Industrial Structure-Tertiary Industry	Carbon Emissions
	(1)	(2)	(3)	(4)
Treat	-0.053** (0.025)	–	0.025** (0.012)	–
Secondary industry×Treat	–	0.002 (0.030)	–	–
Tertiary industry×Treat	–	–	–	-0.005 (0.026)
Control variables	Yes	Yes	Yes	Yes
Urban fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	2968	2945	2968	2945
Adjusted R^2	0.816	0.608	0.809	0.615

Note: Robust standard errors at the city level are in parentheses; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Where CO_{2it} denotes the carbon emissions of the city i in year t, and $Treat_{it}$ denotes whether city i is a low-carbon pilot city in year t, and M_{it} denotes the proxy variables for the mechanism variables in this paper, and $M_{it} \times Treat_{it}$ denotes the interaction of the low-carbon pilot policy and the mechanism variables and their coefficient β_2 is the coefficient focused on in this paper representing the magnitude of the effect of low-carbon pilot policy on urban carbon emissions through the mechanism variables.

Industrial Restructuring Effect

Implementing a low-carbon pilot policy may cause industrial restructuring through government-led and market-regulated approaches, affecting urban carbon emissions. Specifically, in low-carbon pilot cities, the government is inclined to adopt carbon tax and environmental regulation to restrict the development of high pollution, high energy consumption, and low-efficiency industries and to provide financial and policy support to clean energy industries and high-tech industries, which will promote the effective allocation and rational use of resources and thus optimize the industrial structure. Therefore, this paper selects the proportion of value added by a secondary industry to GDP and the proportion added by a tertiary industry to GDP as the proxy variables for industrial structure. The regression results are presented in Table 4. The estimated coefficients in Columns (1) and (3) of the table are statistically significant at the 5% level, and the estimated coefficient in Column (1) is significantly negative. In contrast, the estimated coefficient in Column (3) is significantly positive. It indicates that the low-carbon pilot policy significantly decreases the proportion of the secondary sector and substantially increases the proportion of the tertiary sector, which upgrades the industrial structure. However, the table's estimated coefficients in Columns (2) and (4) are not statistically significant. They suggest that the impact of the industrial structure adjustment on urban carbon emissions is insignificant. It has been shown that industrial restructuring does not significantly impact urban carbon reduction, and the impact may vary depending on the local economic development structure [42].

Technological Innovation Effect

The low-carbon pilot policy will encourage the government to invest more in scientific research and adopt a combination of policy measures, such as green finance, to support green technological innovation financially. On the other hand, under the pressure of environmental regulation, enterprises will take the initiative to upgrade production and increase R&D, reducing their environmental pollution tax burden. In this paper, the total number of patents granted in cities is chosen as a proxy variable for technological innovation, and the regression results are presented in Table 5. The coefficient estimates in Column (1) are positive and statistically significant at the 1% level. It indicates that the low-carbon pilot policy improves urban technological innovation. The estimated coefficient in Column (2) is significantly negative at the 10% level, which indicates that urban technological innovation significantly reduces carbon emissions. Therefore, the low-carbon pilot policy significantly reduces urban carbon emissions through the technological innovation effect.

Energy Saving Effect

Energy consumption in China is dominated by coal, with insufficient high-quality fossil energy such

Table 5. Impact of low-carbon pilot policy on carbon emissions through technological innovation.

Variables	Technological innovation	Carbon emissions
	(1)	(2)
Treat	0.793*** (0.238)	–
Technological Innovation×Treat	–	-0.073* (0.043)
Control variables	Yes	Yes
Urban fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	2968	2854
Adjusted R^2	0.716	0.632

Note: Robust standard errors at the city level are in parentheses; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 6. Impact of low-carbon Pilot Policy on carbon emissions through energy consumption savings.

Variables	Energy consumption	Carbon emissions
	(1)	(2)
Treat	-0.084* (0.043)	–
Energy consumption×Treat	–	0.037* (0.021)
Control variables	Yes	Yes
Urban fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	2968	2945
Adjusted R^2	0.945	0.630

Note: Robust standard errors at the city level are in parentheses; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

as oil and natural gas and low clean energy usage. The unreasonable energy consumption structure has increased China's environmental burden. Implementing a low-carbon pilot policy has reduced urban energy waste and over-consumption, controlled the total energy consumption of industrial production and residents' livelihoods, and reduced urban carbon emissions. In this paper, the urban annual electricity consumption is chosen as a proxy variable for energy consumption, and the results are presented in Table 6. The regression coefficient in Column (1) is negative at a 10% significance level, which indicates that the low-carbon pilot policy significantly reduces urban energy consumption and promotes urban energy conservation. The regression coefficient in Column (2) is positive at a 10% significance level, which indicates that increased energy consumption will increase urban carbon emissions [43, 44]. Therefore, the low-carbon pilot policy significantly reduces urban carbon emissions through the energy conservation effect.

Carbon Sink Effect

A more intuitive effect of the low-carbon pilot policy is reducing the carbon dioxide concentration by increasing the green coverage and urban carbon sink [45]. This paper selects the green area per capita as a proxy variable for the carbon sink effect. The regression results are presented in Table 7. The coefficient estimates in Column (1) are positive and statistically significant at 5%. This study indicates that the low-carbon pilot policy significantly increases urban carbon sinks by increasing green coverage. The estimated coefficient in Column (2) is negative at a 5% significance level, which indicates that the increase in carbon sinks reduces urban carbon emissions. Thus,

Table 7. Impact of low-carbon pilot policy on carbon emissions through carbon sink increase.

Variables	Carbon Sink	Carbon emissions
	(1)	(2)
Treat	0.113** (0.052)	–
Carbon Sink×Treat	–	-0.045** (0.018)
Control variables	Yes	Yes
Urban fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	2968	2945
Adjusted R^2	0.806	0.624

Note: Robust standard errors at the city level are in parentheses; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

the low-carbon pilot policy significantly reduces carbon emissions through the carbon sink effect.

Environmental Governance Investment Effect

Urban environmental governance mainly influences carbon emissions through the scientific disposal of waste and improving sanitation facilities. Specifically, the increase in environmental governance investment will help dispose of municipal waste timelier and more effectively using scientific and clean disposal methods. At the same time, improving sanitation facilities will also decrease waste exposure. All of this will reduce the direct emission of harmful gases. In this paper, urban sanitation investment is chosen as a proxy variable for the effect of environmental governance. The regression results are reported in Table 8. The estimated coefficient in Column (1) is significantly positive at the 10% level, which indicates that the low-carbon pilot policy significantly increases environmental governance investment. The estimated coefficient in Column (2) is significantly negative at the 1% level, which indicates that the increase in environmental governance investment significantly reduces urban carbon emissions. Therefore, the low-carbon pilot policy significantly reduces urban carbon emissions by increasing environmental governance investment.

Heterogeneous Analysis

Depending on city differences, the low-carbon pilot policy may have different carbon reduction effects. This paper further investigates the effects of policies on carbon reduction in cities at different spatial locations and administrative levels.

In terms of spatial locations, because of the different economic development levels in different regions, this paper divides the sample into eastern, central, and western cities. The regression results for these three regions are presented in Table 9. The results in Columns (1) to (3) of the table show that the coefficient estimates are statistically significant at a 10% level in the eastern cities, and the coefficient estimates are not statistically significant in both the central and western cities. This study indicates that the carbon reduction effect of low-carbon pilot policy has spatial differences, i.e., the policy has a significant impact in eastern cities but not in central and western cities. Eastern cities in China have more developed economies and higher technological levels and are more likely to gather resources than central and western cities. So, the carbon reduction effect is significant in the eastern region. Central and Western cities rely more on energy industries in their economic development, and the economic structure and unreasonable industrial structure may lead to an insignificant effect.

In terms of the administrative level, this paper classifies the provincial, vice-provincial, and provincial capitals as high-ranking cities and the rest as low-ranking cities. The regression results are shown in Table 9. The results in Columns (4) and (5) show that the coefficient estimates of high-ranking cities are negative at a 1% significance level. In contrast, the coefficient estimates of low-ranking cities are not statistically significant. This study indicates that the impact of low-carbon pilot policy differs for cities of different ranking levels. High-ranking cities have higher resource utilization efficiency and more capital and technology resources than low-ranking cities. Therefore, high-ranking cities can better enjoy the carbon reduction effects of a low-carbon pilot policy.

Discussion

This paper finds that the low-carbon pilot policy in China significantly reduces carbon emissions in pilot cities by about 24.5%. This result indicates that the low-carbon pilot

Table 8. Impact of low-carbon pilot policy on carbon emissions through environmental governance investment.

Variables	Environmental Governance	Carbon emissions
	(1)	(2)
Treat	0.241* (0.134)	–
Environmental Governance×Treat	–	-0.063*** (0.018)
Control variables	Yes	Yes
Urban fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	2335	2945
Adjusted R^2	0.464	0.622

Note: Robust standard errors at the city level are in parentheses; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 9. Impact of low-carbon pilot policy on cities in different spatial locations and administrative levels.

Variables	Urban Spatial Location			City administrative level	
	Central Cities	Eastern Cities	Western Cities	Non-high-grade cities	High-grade cities
	(1)	(2)	(3)	(4)	(5)
Treat	-0.318 (0.359)	-0.244* (0.131)	-0.152 (0.159)	-0.183 (0.113)	-0.470*** (0.167)
Control variables	Yes	Yes	Yes	Yes	Yes
Urban fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	712	1664	569	2442	489
Adjusted R^2	0.530	0.664	0.670	0.629	0.641

Note: Robust standard errors at the city level are in parentheses; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

policy has achieved its expected effect and reduced urban carbon emissions. It is consistent with the estimated results of Huo et al. (2022) [46] on the impact of low-carbon pilot policy on urban carbon emission reduction.

As one of the possible impact mechanisms of low-carbon pilot policy on carbon emissions [47, 48], industrial restructuring is an important research content to measure the effects of policies. This paper shows that although there is an expected relationship between industrial restructuring and carbon emissions, the empirical results are insignificant. Shen et al. (2018) [49] divide the carbon reduction mechanism of the low-carbon pilot policy in Beijing into different stages. The results show that from 1991 to 2004, industrial restructuring was the main contributor to reducing carbon emissions, but from 2004 to 2022, energy intensity was the main influencing factor to curb carbon emissions. This study indicates that industrial restructuring may have different carbon reduction effects depending on different economic development characteristics at different periods. In addition, differences in economic structure among different cities also make the carbon reduction effect of industrial restructuring different [50]. Zhang et al. (2020) [51] studied the effect of industrial structure on carbon intensity of 281 cities in China from 2006 to 2016, and the results show that the effect of industrial restructuring on carbon intensity is not as significant as expected, which is similar to the findings of this paper.

In this paper, technological innovation has also been verified as one of the impact mechanisms of low-carbon pilot policy on carbon emissions. Wang et al. (2022) [17] and Zou et al. (2022) [52] further explain that the policy improves technological innovation by increasing government investment in technology and encouraging enterprises to improve production technology, to provide technical support for urban low-carbon development. On energy conservation mechanism, Zhou et al. (2022) [53] argue that the low-carbon pilot policy reduces coal consumption intensity and significantly reduces carbon emissions, which is consistent with the results in this study. Moreover, Yang et al. (2017) [54] propose that clean energy substitution and efficiency improvement also effectively reduce carbon emissions in addition to energy conservation. This paper also argues that the policy reduces carbon emissions by increasing carbon sink. Similar to this result, Zhu et al. (2022) [55] conclude that climate policies generally have a positive impact on increasing carbon sink, and the impact has a spillover effect. On the environmental governance investment mechanism, consistent with the results of this paper, Yu et al. (2023) [56] argue that the government's attention to environmental governance increases enterprises' environmental investment, promoting urban green development.

This paper further verified that different city characteristics lead to regional heterogeneity in the policy's carbon reduction effect. This paper shows that the policy's carbon reduction effect is significant in eastern cities but not in central and western cities. This finding is also verified in the study by Liu et al. (2022) [57]. The probable reason is that eastern cities are more market-oriented, and companies are more motivated to participate in carbon emission control actions under the incentive of market mechanisms [57]. While most existing studies classify cities based on population size, this paper classifies cities according to their administrative levels. The empirical results demonstrate that the carbon reduction effect of the policy is more significant in high-ranking cities, which is consistent with the study of Ye et al. (2023) [58], arguing that provincial capitals play leading roles in reducing carbon emissions. Cities with higher administrative ranking are more capable of administrative resource agglomeration, economic resource agglomeration, public resource agglomeration, and human resource aggregation [59, 60]. The resource agglomeration effect is conducive to factor flow, technological innovation, and economic structure optimization and is better for fostering low-carbon regional growth and reducing carbon emissions [61]. That explains the findings of this paper to some extent that high-ranking cities tend to be more able to gather resources, promote green technological innovation, etc., and therefore, their carbon reduction effect is more significant.

This paper evaluates the direct impact of low-carbon pilot policy on carbon emissions. It investigates the impact mechanisms of low-carbon pilot policy on carbon reduction in China, which provides a reference for other countries and regions to develop carbon reduction policies. In addition, this paper points out differences in policy effects among cities at different administrative levels. When considering the spatial location differences in the effects of policies on carbon reduction, policymakers should also pay attention to the differences in the effects of cities at different administrative levels. For China, while enhancing the cross-regional linkage among eastern, central, and western cities, it is also necessary to strengthen cooperation and communication among cities at different regional administrative levels.

Conclusions

This paper focuses on the impact of low-carbon pilot policy on urban carbon emissions. Based on the sample data of 212 cities, the article uses the DID method to empirically analyze the impact of low-carbon pilot policy on urban carbon emissions. Further, it explores the impact mechanisms of low-carbon pilot policy on carbon emissions and the heterogeneous effects in different regions. Through the above research, the following main conclusions are drawn in this paper:

(1) The low-carbon pilot policy significantly reduces urban carbon emissions. Pilot cities reduce carbon emissions by 24.5% compared to non-pilot cities after the policy is implemented. This result is still valid after the parallel trend and comprehensive robustness tests.

(2) The low-carbon pilot policy has significantly reduced urban carbon emissions through technological innovation, energy conservation, carbon sinks, and environmental governance investment. The low-carbon pilot policy has promoted green technological innovation, reduced urban energy consumption, and increased urban green space and environmental governance investment. Through the above effects, the policy has effectively reduced urban carbon emissions. However, the impact of a low-carbon pilot policy on carbon emissions reduction by adjusting industrial structure is not statistically significant.

(3) The impact of low-carbon pilot policy on carbon emissions varies across regions. Among cities in different spatial locations, the effect of the policy on carbon emission reduction in eastern cities is more significant than in central and western cities. Among cities of different administrative levels, the policy significantly reduces carbon emissions in high-ranking cities. In contrast, the effect of the policy on low-ranking cities is insignificant.

Based on the above findings, the following policy implications are proposed:

(1) The carbon reduction effect of the low-carbon pilot policy is significant and can be referenced elsewhere in China. The results of this paper show that the policy has significantly reduced urban carbon emissions and promoted the low-carbon urban transformation, which not only meets the needs of China to cope with climate change but also provides a reference for global green sustainable development. Therefore, the low-carbon development experience of the pilot cities should be summarized and promoted nationwide in due course.

(2) To promote industrial structure's green and low-carbon transformation and establish a clean and intelligent modern industrial system. The mechanism test results of this paper show that the industrial structure adjustment fails to achieve the expected carbon reduction effect. For industries with high pollution and energy consumption, the pilot cities should adopt comprehensive measures to promote traditional industries' intelligent transformation and green development. At the same time, the pilot cities should also actively develop green, high-tech, and clean energy industries to reduce carbon emissions in industry, transportation, construction, energy, and other sectors.

(3) Different low-carbon policies should be formulated according to local conditions and promote cross-regional cooperation. Local governments formulate and implement a low-carbon pilot policy with weak constraints according

to their actual conditions. The results of the heterogeneity analysis in this paper also show that the effects of the low-carbon pilot policy on carbon emission reduction are different in different regions. Therefore, when learning from the experience of the pilot cities, local governments should set reasonable development goals and implement them effectively according to the local economic structure and natural conditions. At the same time, it is also essential to strengthen the linkage and cooperation between regions and enhance the demonstration effect of pilot areas. Regions with weak low-carbon development capabilities can selectively undertake the transfer of clean energy industries and high-tech industries from eastern and high-ranking cities, and strengthen the exchanges of core technologies and advanced experience among regions.

There are still some limitations in this paper that need further study. (1) Although this paper considers the sample's representativeness and selects 212 cities for the study, there are differences in the characteristics of different cities. Therefore, the results of this paper should be interpreted with caution. (2) Due to data acquisition limitations, this study could not conduct more detailed research at the micro level. Future research needs to analyze the policy impact mechanism from the micro-enterprise level further. (3) The policy effect has a time lag. In addition, the low-carbon pilot policy is in the development stage, and future research should be carried out from a richer perspective as the policy effects are still to be revealed. Researchers should strive to obtain more comprehensive sample data and cover a wider temporal and spatial scope to enhance the reliability of empirical results.

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Conflicts of interest

No conflict of interest exists in the submission of this manuscript, and all authors have approved the manuscript for publication. I want to declare on behalf of my co-authors that the work described is original research that has not been published previously and is not under consideration for publication elsewhere.

References

1. AVERCHENKOVA A., FANKHAUSER S., FINNEGAN J.J. The impact of strategic climate legislation: evidence from expert interviews on the UK Climate Change Act. Climate Policy. **21** (2), 251, **2021**.
2. LOCKWOOD M. The political sustainability of climate policy: The case of the U.K. Climate Change Act. Global Environmental Change. **23** (5), 1339, **2013**.
3. HOLMAN C., HARRISON R., QUEROL X. Review of the efficacy of low emission zones to improve urban air quality in European cities. Atmospheric Environment. **111**, 161, **2015**.
4. WOLFF H. Keep your clunker in the suburb: low-emission zones and adoption of green vehicles. The Economic Journal. **124** (578), 481, **2014**.
5. TAKASE K., SUZUKI T. The Japanese energy sector: Current situation, and future paths. Energy Policy. **39** (11), 6731, **2011**.
6. ZAIM O., GAZEL T.U., AKKEMIK K.A. Measuring energy intensity in Japan: A new method. European Journal of Operational Research. **258** (2), 778, **2017**.
7. XU J., SHE, S., LIU, W. Leading the Green Transformation of Production and Life Style through "Double Carbon Target". Theoretical Investigation. **6**, 132, **2021**.
8. YANG W., ZHU C., YANG Y. Does Urban Digital Construction Promote Economic Growth? Evidence from China. Economies. **12** (3), 59, **2024**.
9. CHENG J., Y.I. J., DAI S., XIONG Y. Can low-carbon city construction facilitate green growth? Evidence from China's pilot low-carbon city initiative. Journal of Cleaner Production. **231**, 1158, **2019**.
10. ZHANG H., HUANG L., ZHU Y., SI H., HE X. Does low-carbon city construction improve total factor productivity? Evidence from a quasi-natural experiment in China. International Journal of Environmental Research and Public Health. **18** (22), 11974, **2021**.
11. YANG W., PAN L., DING Q. Dynamic analysis of natural gas substitution for crude oil: Scenario simulation and quantitative evaluation. Energy. **282**, 128764, **2023**.
12. SHAN Y., LIU J., LIU Z., SHAO S., GUAN D. An emissions-socioeconomic inventory of Chinese cities. Scientific Data. **6** (1), 1, **2019**.
13. SONG H., SUN Y., CHEN D. Assessment for the effect of government air pollution control policy: empirical evidence from "low-carbon city" construction in China. World. **35** (6), 95, **2019**.
14. WANG J., LIU Z., SHI L., TAN J. The impact of low-carbon pilot city policy on corporate green technology innovation in a sustainable development context—evidence from Chinese listed companies. Sustainability. **14** (17), 10953, **2022**.
15. CHEN L., HE F. Measurements and factors of carbon emission efficiency. Polish Journal of Environmental Studies. **26** (5), 1963, **2017**.
16. TIAN L., LIU C. "Peer" Institutional Pressure and Enterprise Green Innovation: Spillover Effects of Environmental Pilot Policy. Business and Management Journal **43** (6), 156, **2021**.
17. WANG T., SONG Z., ZHOU J., SUN H., LIU F. Low-carbon transition and green innovation: evidence from pilot cities in China. Sustainability. **14** (12), 7264, **2022**.
18. YANG W., ZHENG X., YANG Y. Impact of environmental regulation on export technological complexity of high-tech industries in Chinese manufacturing. Economies. **12** (2), 50, **2024**.
19. Q.I. S.-Z., ZHOU C.-B., LI K., TANG S.-Y. Influence of a pilot carbon trading policy on enterprises' low-carbon innovation in China. Climate Policy. **21** (3), 318, **2021**.
20. ZHAO Z., CHENG Z., LV D. Has the national low-carbon strategy increased companies' total factor productivity? A quasi-natural experiment based on the low-carbon city pilot. Industrial Economics Research. **2021** (6), 101, **2021**.
21. DONG M. Analysis of the Net Emission Reduction Effect of the Industrial Pollutants in Low-carbon Pilot Cities Based on Synthetic Control Method. Journal of Beijing Institute of Technology (Social Sciences Edition). **23** (5), 16, **2021**.
22. LU J., WANG X., LIU L. Industrial structure upgrading effect of low carbon city policy: quasi-natural experimental

research based on low-carbon city pilot. Journal of Xi'an Jiaotong University (Social Sciences). **40** (2), 104, **2020**.
23. SHE S., WANG Q., ZHANG A. Technological innovation, industrial structure and urban GTFP — channel test based on national low-carbon city pilots. Journal of Economics & Management Research. **41**, 44, **2020**.
24. WANG L., SHAO J., MA Y. Does China's low-carbon city pilot policy improve energy efficiency? Energy. **283**, 129048, **2023**.
25. BAYER P., AKLIN M. The European Union emissions trading system reduced CO2 emissions despite low prices. Proceedings of the National Academy of Sciences. **117** (16), 8804, **2020**.
26. MURRAY B., RIVERS N. British Columbia's revenue-neutral carbon tax: A review of the latest "grand experiment" in environmental policy. Energy Policy. **86**, 674, **2015**.
27. WAKIYAMA T., ZUSMAN E. The impact of electricity market reform and subnational climate policy on carbon dioxide emissions across the United States: A path analysis. Renewable and Sustainable Energy Reviews. **149**, 111337, **2021**.
28. FUINHAS J.A., MARQUES A.C., KOENGKAN M. Are renewable energy policies upsetting carbon dioxide emissions? The case of Latin America countries. Environmental Science and Pollution Research. **24**, 15044, **2017**.
29. WANG S., HUANG Y., ZHOU Y. Spatial spillover effect and driving forces of carbon emission intensity at the city level in China. Journal of Geographical Sciences. **29**, 231, **2019**.
30. XU Y.-Q., CHENG Y., WANG J.-J., LIU N. Spatio-temporal evolution and influencing factors of carbon emission efficiency in low carbon city of China. Journal of Natural Resources. **37** (5), 1261, **2022**.
31. ZHOU D., ZHOU F., WANG X. Impact of low-carbon pilot policy on the performance of urban carbon emissions and its mechanism. Resources Science. **41**, 546, **2019**.
32. YU X., CHEN N., LI M. Research on carbon emission characteristics and reduction pathways of low-carbon pilot cities in China. China Population, Resources and Environment. **30** (7), 1, **2020**.
33. XU J., CUI J.B. Low-carbon cities and firms' green technological innovation. China Industrial Economics. **12**, 178, **2020** [In Chinese].
34. ZHANG B.-B., ZHOU J.-T., YAN Z.J. Low-Carbon City Pilot Policies and Total Factor Energy Efficiency Improvement: Quasi-Natural Experiment from the Implementation of Three Batches of Pilot Policies. Economic Review. **5**, 32, **2021**.
35. WANG L., ZHAO Y. Policy evaluation of the low-carbon pilot cities: Effects and mechanisms. Geographical Research. **41**, 1898, **2022**.
36. YANG Y., ZHANG X., WU T. Does Public Participation Reduce Regional Carbon Emissions? A Quasi-Natural Experiment from Environmental Information Disclosure in China. Polish Journal of Environmental Studies. **32** (2), 1899, **2023**.
37. WANG F., WU L., YANG C. Driving factors for growth of carbon dioxide emissions during economic development in China. Research in Economics. **45** (2), 123, **2010**.
38. ZHAO Q., LI Y., YAN Q., ZHANG L. Does Technical Progress Stimulate the Low-Carbon Transformation Process in China? A Provincial Aspect. Polish Journal of Environmental Studies. **29** (1), 463, **2020**.
39. JACOBSON L.S., LALONDE R.J., SULLIVAN D.G. Earnings losses of displaced workers. The American Economic Review. 685, **1993**.
40. FERRARA E.L., CHONG A., DURYEA S. Soap operas and fertility: Evidence from Brazil. American Economic Journal: Applied Economics. **4** (4), 1, **2012**.
41. LI W., LI Y. Does industrial policy promote corporate investment. China Industrial Economics. **5** (9), 122, **2014**.
42. ZHENG X., WANG R., DU Q. How does industrial restructuring influence carbon emissions: City-level evidence from China. Journal of Environmental Management. **276**, 111093, **2020**.
43. JIANG X.-T., WANG Q., LI R. Investigating factors affecting carbon emission in China and the USA: A perspective of stratified heterogeneity. Journal of Cleaner Production. **199**, 85, **2018**.
44. SUN W., HUANG C. Predictions of carbon emission intensity based on factor analysis and an improved extreme learning machine from the perspective of carbon emission efficiency. Journal of Cleaner Production. **338**, 130414, **2022**.
45. LIN B., GE J. Valued forest carbon sinks: How much emissions abatement costs could be reduced in China. Journal of Cleaner Production. **224**, 455, **2019**.
46. HUO W., QI J., YANG T., LIU J., LIU M., ZHOU Z. Effects of China's pilot low-carbon city policy on carbon emission reduction: a quasi-natural experiment based on satellite data. Technological Forecasting and Social Change. **175**, 121422, **2022**.
47. GE X., QI W. Analysis of CO2 Emission Drives Based on Energy Consumption and Prediction of Low Carbon Scenarios: a Case Study of Hebei Province. Polish Journal of Environmental Studies. **29** (3), 2185, **2020**.
48. LI H., MA Q., ZHANG P., ZHANG M., WANG D. What Affects Carbon Emission Performance? An Empirical Study From China. Polish Journal of Environmental Studies. **31** (6), 5751, **2022**.
49. SHEN L., WU Y., LOU Y., ZENG D., SHUAI C., SONG X. What drives the carbon emission in the Chinese cities? — A case of pilot low carbon city of Beijing. Journal of Cleaner Production. **174**, 343, **2018**.
50. ZHANG X., ZHU H., SANG B., GUO L. The incompatibility between industrial restructuring and low-carbon economy: a comprehensive analysis. Environmental Science and Pollution Research. **30** (36), 85611, **2023**.
51. ZHANG F., DENG X., PHILLIPS F., FANG C., WANG C. Impacts of industrial structure and technical progress on carbon emission intensity: Evidence from 281 cities in China. Technological Forecasting and Social Change. **154**, 119949, **2020**.
52. ZOU C., HUANG Y., WU S., HU S. Does "low-carbon city" accelerate urban innovation? Evidence from China. Sustainable Cities and Society. **83**, 103954, **2022**.
53. ZHOU Q., CUI X., NI H., GONG L. The impact of environmental regulation policy on firms' energy-saving behavior: a quasi-natural experiment based on China's low-carbon pilot city policy. Resources Policy. **76**, 102538, **2022**.
54. YANG D., LIU B., MA W., GUO Q., LI F., YANG D. Sectoral energy-carbon nexus and low-carbon policy alternatives: A case study of Ningbo, China. Journal of Cleaner Production. **156**, 480, **2017**.
55. ZHU H., CAI Y., LIN H., TIAN Y. Impacts of Cross-Sectoral Climate Policy on Forest Carbon Sinks and Their Spatial Spillover: Evidence from Chinese Provincial Panel Data. International Journal of Environmental Research and Public Health. **19** (21), 14334, **2022**.
56. YU D., HU K., HAO Y. The effect of local government environmental concern on corporate environmental

investment: evidence from China. Sustainability. **15** (15), 11604, **2023**.
57. LIU X., LI Y., CHEN X., LIU J. Evaluation of low carbon city pilot policy effect on carbon abatement in China: An empirical evidence based on time-varying DID model. Cities. **123**, 103582, **2022**.
58. YE L., WANG G., ZHANG Y., SUN S., QIN Y., SUN L., WU S. Spatiotemporal Evolution and Driving Forces of the Carbon Emissions of the Yangtze River Delta Urban Agglomeration. Polish Journal of Environmental Studies. **32** (3), 2417, **2023**.
59. JIA C., GE Y. Differences in Urban Administration Level, Resource Aggregation Capacity and House Price Level. Research on Financial and Economic Issues. **10**, 131, **2015**.
60. SU L. Temporal-spatial evolution characteristics and influencing factors of urban carbon emissions in China. Polish Journal of Environmental Studies. **32** (3), 2309, **2023**.
61. WANG L., ZHAO Y. Policy evaluation of the low-carbon pilot cities: Effects and mechanisms. Geographical Research. **41**, 1898, **2022**.