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Does the low-carbon pilot cities policy make a difference to the carbon intensity reduction?

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ABSTRACT

The *low-carbon pilot cities policy* (LCPCP) aims to stimulate economic growth and ensure the attainment of greenhouse gas emission reduction targets to address climate change. China issued the LCPCP in 2010 and steadily expanded the size of its pilot zones. This study builds a quasi-natural experiment based on China's LCPCP and a difference-in-difference model employing urban carbon intensity data over a 10-year period beginning in 2007 to examine the implementation repercussions of the LCPCP. According to the findings, the LCPCP has significantly reduced the carbon intensity of pilot cities. Additionally, an analysis of heterogeneity suggests that the LCPCP is more prevalent in regions with higher concentrations of secondary industries. Moreover, the mechanism reveals that the decarbonization program reduces carbon intensity through technological innovation, particularly in eastern China. In conclusion, our findings provide strong support for the operation and promotion of China's LCPCP as well as guidance and support for China's goal of reducing carbon emissions.

1. Introduction

Climate change is a severe global threat, and a better response to it remains crucial and urgent for the entire human race (D'Orazio and Valente, 2019; Birkmann et al., 2022; Feng et al., 2023). Reducing greenhouse gas emissions has always played an important role as one of the fundamental strategies for mitigating climate change (Gowdy, 2008; Duan et al., 2019b). As the largest developing nation, a CO_2 emitter, and an energy consumer, China's effective response to climate change is vital for achieving global carbon reduction, especially as its relevant emission reduction experience can provide a reference for developing countries in the process of industrialization (Duan et al., 2019a; Ren et al., 2021a; Lee and Wang, 2022). China currently faces international responsibility to achieve sustainable development and reduce its carbon intensity. Since 2010, China has included carbon intensity as a constraint indicator in its economic development plans. For example, the Chinese government announced that by 2030, the carbon emission intensity per unit of GDP would be reduced by 60–65% compared to 2005 (Gao et al., 2022; Tian et al., 2022). To this end, China has implemented a

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series of measures and methods, such as adjusting its energy structure to reduce carbon intensity (Xue et al., 2023). Although the above measures and methods have greatly reduced carbon intensity, China's economic development relies heavily on infrastructure investment capital and physically driven capital stock, resulting in China's carbon intensity currently ranking first globally (Fan et al., 2023), and reversing climate change remains elusive (Xue et al., 2023; Liu et al., 2023). Therefore, exploring the impacts of various policies and plans on carbon intensity is crucial.

Developing sound, low-carbon, and sustainable development policies to achieve various carbon reduction goals while ensuring stable economic growth has always been the focus of politicians, scholars, and the public (Chavas et al., 2016; Dogan and Turkekul, 2016; Rengs et al., 2020). To this end, the Chinese government formulated several policies and plans to address climate vulnerability (Lee and Wang, 2022). For example, China has completely incorporated carbon emission reduction into its overall national economic and social growth policy and suggested a "30•60 double carbon goal" as an objective.[1] China's low-carbon pilot cities policy (LCPCP), a highly representative and relevant policy, was issued by China's National Development and Reform Commission (NDRC) in 2010 (Yang et al., 2023). The LCPCP promotes economic development and mitigates climate change (Liu et al., 2020). Moreover, China's rapid urbanization has paralleled the 250% increase in primary energy demand over the past decade, and urban regions have become key to China's energy and carbon emission reductions (Khanna et al., 2014; Zhu and Lee, 2022). Consequently, evaluating the LCPCP's policy ramifications is vital to gaining a deeper understanding of its mechanics. Although various studies have examined the impact of LCPCP on carbon emissions (Shen et al., 2018; Sun and Wang, 2021), to meet the dual carbon aim, we focus on carbon emissions and carbon intensity (Zhu et al., 2015). Similarly, it is crucial to determine from a theoretical and empirical basis if the government's "top-down" LCPCP has produced the desired objectives in combating climate change (Xu et al., 2022). However, relatively few studies have been conducted on this topic.

In addition, because of the implementation of several environmental protection policies in China in recent years, such as green finance policies, environmental courts, and carbon emission trading schemes, the effectiveness of China's environmental regulatory policies has attracted serious concern from both academics and policymakers (Hering and Poncet, 2014; Wang and Chang, 2014; Wu et al., 2020; Huang and Lei, 2021). To exclude the influence of survey data and individuals on the estimation of policy effects, several researchers have recently viewed the LCPCP as a natural experiment and developed difference-in-difference (DID) models to examine LCPCP's effects (Berrone et al., 2013; Liu et al., 2020; Cheng et al., 2019; Tang et al., 2018; Chen et al., 2021; Song et al., 2020; Yu and Zhang, 2021). For example, Cheng et al. (2019), utilizing data from the second round of low-carbon pilot cities in China, investigate the impact of the LCPCP on green growth and find that this policy increased urban green total factor productivity. Chen et al. (2021) analyse if and how LCPCP influences firms' total factor productivity (TFP) using PSM-DID (Propensity Score Matching-Difference-in-Difference) models and find that LCPCP significantly contributes to the rise in local firms' TFP. Although most researchers affirm the positive influence of environmental regulations on regional green economic growth, there is no consensus on the policy's ultimate effect (Liu et al., 2020). In particular, compared to the above measures and methods, the role of LCPCP in reducing carbon intensity has rarely been analsyed or discussed.

Moreover, industrialization and urbanization have increased energy consumption and carbon emissions (Li and Lin, 2015). Given that urbanization will predominantly occur in developing countries over the next decade, carbon emissions from these cities will further increase (Tang et al., 2021a). Consequently, the international community broadly recognizes the significance of cities in developing nations in reducing carbon emissions, which is the main method for mitigating climate change (Zhao et al., 2019; Tang et al., 2021a). However, the academic community remains divided on the innovation incentive impact of the LCPCP as an environmental regulatory policy. Specifically, Tian et al. (2021) find, contrary to the *Porter Hypothesis*, that the LCPCP has a crowding-out effect on urban non-green innovation. According to Lu et al. (2020), the LCPCP positively affects technological innovation. The LCPCP seeks to synchronize regional environmental impacts with economic growth (NDRC, 2010). Meanwhile, the trend toward complete coverage of low-carbon plans raises the question of whether the LCPCP has played a role in these cities (Tang et al., 2018). Therefore, discussing the LCPCP's innovation incentive mechanism in depth is essential, which blends market incentives and command control. Therefore, does the LCPCP lower carbon intensity in urban areas? If the LCPCP reduces carbon intensity in urban areas, what is the underlying mechanism? Notably, there is a need for greater discussion on innovation incentive mechanisms. In addition, does the impact of the LCPCP on urban carbon intensity vary among the pilot cities? The answers to these questions will aid in comprehending the efficacy of LCPCP implementation at this level in China and provide policy implications depending on local variables that will assist China in attaining its dual-carbon goal.

To answer the aforementioned questions, this study uses panel data from China's first and second carbon pilot cities from 2007 to 2017 to explore the impact and mechanism of the LCPCP on carbon intensity using a DID model. The research results show that (1) the LCPCP significantly reduces the carbon intensity of pilot cities; (2) the LCPCP is more common in regions with high concentrations of secondary industry; and (3) decarbonization programs reduce carbon intensity through technological innovation, especially in eastern China.

Our work contributes to the current body of knowledge in the following respects:

(1) Using the LCPCP as a starting point, this study explores its effect on carbon intensity for the first time and adds to existing research on carbon intensity. Previous studies on the LCPCP in China focused on low-carbon development and carbon

[1] President Xi Jinping declared on September 22, 2020, during the general discussion of the 75th United Nations General Assembly, that China's carbon dioxide emissions will attempt to peak before 2030 and become "carbon neutral" by 2060. (Yang et al., 2021)

emissions. However, research on LCPCPs is scarce (Song et al., 2021). Most past research has qualitatively evaluated the impact of LCPCP, but no thorough empirical examination of the impact of LCPCP has been conducted (Liu et al., 2020).

(2) We choose carbon intensity to depict the LCPCP's impact because it strives to combine regional environmental impacts with economic growth. This is principally because carbon intensity reflects economic growth and environmental conservation in greater detail than carbon emissions. In addition, we consider provincial heterogeneity when assessing the impact of the LCPCP on carbon intensity.

(3) By investigating the effects of both direct and indirect mechanisms from a theoretical approach, we analyze the specific impact path of the LCPCP on carbon intensity using the *Porter Hypothesis* as a basis, gaining a greater knowledge of the consequences of environmental regulation. A number of robustness tests are also conducted to further describe the LCPCP's implementation impact and to successfully avoid the systematic error and deviation estimation that may occur when evaluating environmental regulations.

(4) This paper, which is based on the LCPCP study, shows that creating low-carbon cities can provide the Chinese government with useful guidance as it examines environmental laws and regulations to realize the double dividend of economy and environment and serve as a policy reference for China to achieve its double-carbon goal.

The paper proceeds as follows. Section 2 outlines institutional background and hypothesis development, while Section 3 details the data and methodologies. Section 4 presents and discusses the results. The conclusion and policy implications are presented in Section 5.

2. Institutional background and hypothesis development

2.1. Institutional background of the LCPCP

In order to better deal with the severe domestic environmental challenges and the enormous pressure from the international community, as well as pursue green transformation and high-quality development, the Chinese government introduced a series of low-carbon strategies to minimize greenhouse gas emissions, especially carbon emissions. (Ren et al., 2021b; Sun, 2022). Cities consume 75% of the world's energy and create more than 70% of carbon emissions since they are the hub of people, transportation, industry, and infrastructure (Huo et al., 2022); at the same time, the per capita energy consumption in cities is three times that of rural areas (excluding non-commercial energy such as biomass). Consequently, urban areas significantly impact global carbon emissions (Williams, 2007; Zhu and Lee, 2022). China's urbanization rate is predicted to reach 75% by 2050, with approximately 13 million people moving from rural to urban areas annually (Berrone et al., 2013). Creating low-carbon cities is crucial for decreasing China's Carbon emission growth. Consequently, NDRC issued the "*Notice on the Implementation of Low-Carbon Pilot Province and Low-Carbon Pilot City Program*" in 2010, selecting the first round of low-carbon pilot locales to achieve the stated goals (NDRC, 2010). The NDRC announced the second and third groups of low-carbon pilot regions in 2012 and 2017, respectively (NDRC, 2012, 2017). As part of an economic plan prepared by the country's highest policy-making and coordinating authority, implementing LCPCP will likely set a pattern for the future development of low-carbon cities in China and other developing countries.

The LCPCP combines command control and market incentive-based environmental monitoring tools (Chen et al., 2021). Theoretically and empirically, a stringent environmental policy is viewed as an effective strategy for boosting the competitiveness of firms (Kamana, 2021). Porter (1991) was the first to reveal this fact, hypothesising that strict environmental regulations can positively affect the innovation and competitiveness of businesses by enhancing their efficiency. *Porter's theory* is predicated on the idea that pollution is frequently a waste of resources and that reducing pollution can increase the productive use of resources. Porter and Van der Linde (1995) conduct more empirical research with this perspective. They believe that reducing pollution may increase the productive use of resources; stricter environmental regulations would avoid environmental degradation and increase firms' market share. Numerous studies support the *Porter Hypothesis* (Skoczkowski et al., 2018; Xie et al., 2017; Rubashkina et al., 2015; Ambec et al., 2013; Hamamoto, 2006). Environmental oversight is regarded as a win-win tool that can improve environmental quality and commercial output (Fu and Jian, 2021). Nonetheless, for a number of scholars, the *Porter Hypothesis* remains a contested gray area. In order to decrease pollution, environmental regulations may require firms to distribute specific factor inputs. This may be ineffective and not helpful in boosting productivity or efficiency from an enterprise perspective (Greenstone et al., 2012; Gray, 1987; Rogge et al., 2011).

The Chinese government put forth the LCPCP in recognition of the crucial role that cities play in preventing future increases in energy use and carbon emissions. Setting energy conservation and emission reduction targets, creating low-carbon development support policies, and promoting a low-carbon green lifestyle are the three main responsibilities of LCPCP, which aims to help China

Table 1
Distribution of pilot cities and control group.

Date of implementation	Pilot cities	Control cities
2010	Tianjin, Chongqing, Shenzhen, Xiamen, Hangzhou, Nanchang, Guiyang, Baoding, Shenyang, Dalian, Xian	Harbin, Changchun, Zhangjiakou, Tangshan, Taiyuan, Changzhi, Jinan, Dezhou, Zhengzhou, Yangzhou, Nanjing, Hefei, Wuxi, Xianning, Changsha, Chengdu, Jiujiang, Longyan, Zhuhai, Fuzhou, Shaoxing
2012	Beijing, Shanghai, Shijiazhuang, Qinhuangdao, Jincheng, Suzhou, Zhenjiang, Ningbo, Wenzhou, Qingdao, Wuhan, Guangzhou, Guangyuan, Zunyi, Kunming, Urumchi	

reach its goal of reducing greenhouse gas emissions by lowering carbon emissions per unit of gross domestic product (GDP) in pilot cities (Sun and Wang, 2021). In 2010, the Chinese government launched a demonstration project in five pilot provinces and eight pilot cities to promote the growth of low-carbon cities. The eight low-carbon pilot cities include Tianjin, Baoding, Hangzhou, Chongqing, Nanchang, Guiyang, Xiamen, and Shenzhen, while the five low-carbon pilot provinces include Yunnan, Guangdong, Hubei, Shaanxi, and Liaoning (NDRC, 2010). Subsequently, in 2012 and 2017, respectively, the second and third rounds of low-carbon pilot cities were announced. The LCPCP aims to raise awareness of the benefits of choosing a low-carbon development path and help the country develop expertise in green development across various fields and industries. These projects demonstrate the Chinese government's commitment to low-carbon economic growth. Thus, it is indisputable that LCPCP will affect carbon intensity. However, will LCPCP ultimately negatively or positively impact carbon intensity? Will this impact vary depending on the characteristics and location of different regions? And through what mechanism does LCPCP affect carbon strength? These are questions that, to our knowledge, have not been addressed in the research to date. Therefore, this study evaluates the impact of the first and second rounds of LCPCP on carbon intensity due to data limitations and the fact that the third round of LCPCP has not been implemented for a sizable amount of time (See Table 1).

2.2. Hypothesis development

Carbon intensity is both directly and indirectly affected by the LCPCP. Numerous researchers have demonstrated that environmental management influences carbon intensity directly through direct processes (Zhang et al., 2020b; Hou et al., 2018; Yang et al., 2020).

The LCPCP influences carbon intensity via four indirect mechanisms: innovation, foreign direct investment (FDI), energy structure and industrial structure, and coordination mode change.

First, environmental legislation will affect innovation (Liu et al., 2020), encouraging firms to innovate and supporting the *Porter Hypothesis* (Rubashkina et al., 2015). Moreover, innovation influences carbon emissions (Huang et al., 2018; Gu et al., 2020; Zhang et al., 2020a; Huang et al., 2020, 2021). In the long term, the increase in production costs caused by the LCPCP may support and stimulate firm investment in green innovation, culminating in a change in carbon intensity.

Second, the LCPCP can affect carbon intensity through foreign direct investment (FDI). FDI from polluting industries is attracted to nations with liberal environmental restrictions, which significantly affects the location selection of FDI (Chung, 2014; Cheng et al., 2018; Dong et al., 2021). Introducing innovative industrial technology and management experience through FDI can also play an important role in lowering carbon intensity (Bi and Yang, 2012; Shao, 2018). Specifically, foreign investment in low-carbon technologies can reduce carbon intensity under environmental constraints (Zhang et al., 2020b). Consequently, the adoption of the LCPCP will influence FDI, resulting in a change in carbon intensity.

Third, environmental regulation will influence the energy structure and industrial structure, affecting carbon intensity (Kheder and Zugravu, 2012; Zhou and Feng, 2017; Zhang et al., 2019; Wang et al., 2019; Du and Li, 2020). (Cole et al., 2005; Reddy and Ray, 2010; Ren et al., 2020). Specifically, the LCPCP may impact energy consumption and structure, leading to a change in urban energy consumption and, as a result, urban carbon intensity.

Fourth, the LCPCP could improve cooperation across government ministries, such as economics, energy, and the environment, to ensure that green and low-carbon development projects may be financed with financial resources. To encourage firms and citizens to adopt low-carbon and energy-efficient lifestyles, many ministries simultaneously promote the importance of low-carbon economic development through a range of means. In order to reduce carbon emissions, the implementation of the LCPCP will encourage individuals to actively choose low-carbon products and modes of transportation in accordance with the concept of low-carbon living. The LCPCP trial pushes the government, businesses, and households to reduce energy use and, as a result, urban carbon intensity (Sun and Wang, 2021).

Given the above considerations, we thus propose the following hypotheses:

Hypothesis 1. Implementing the LCPCP will promote the reduction of urban carbon intensity.

Hypothesis 2. The LCPCP has a heterogeneous impact on the carbon intensity of urban areas.

3. Data and methods

3.1. Variable and data

3.1.1. Carbon intensity

This study investigates annual panel data sets for the first and second rounds of carbon pilot cities in China from 2007 to 2017. Carbon intensity, which measures carbon emissions per unit of GDP, is the dependent variable. Carbon emission calculation is essential to the calculation of carbon intensity. Consequently, with reference to past studies (IPCC, 2007; Zhang et al., 2020a), the following formula is utilized to determine carbon emissions:

$$CI = \sum_{i}^{8} CI_i = \sum_{i}^{8} E_i \times NCV_i \times CEF_i \times COF_i \times \frac{44}{12} \quad (1)$$

where CI is the carbon emission generated by the consumption of fossil fuel $I(i = 1,2,\cdots,8)$, E_i denotes the amount of fossil fuel i burned, NCV_i is the low calorific value, CEF_i represents the carbon content provided by IPCC, and COF_i represents the rate of carbon oxidation. The GDP and carbon emission figures presented above were obtained from the *China Provincial Statistical Yearbook, China Statistical Yearbook*, and *China Energy Statistical Yearbook*. Finally, the foregoing procedure yields the carbon intensity value.

3.1.2. Control variables

Using Feng et al. (2021) and Zhou et al. (2019), we adjust for a vector of other urban variables that have been demonstrated to influence carbon intensity.: economic structure (as proxied by the percentage of the output value of the secondary industry, *Second*, and the third industry, *Third*), local economic development (as measured by a city's per capita GDP, *Pergdp*), the natural logarithm of the resident population (*Lnpop*), and the average annual (*Lnpcon*). All of these control variable data are from the *China Provincial Statistical Yearbook*, the *China Statistical Yearbook*, and the *China City Statistical Yearbook*, and these data are also from 2007 to 2017.

3.2. Sample

Due to limitations in data availability and comparability of different factors such as economic development across cities, following Feng et al. (2021), we choose a sample of 48 cities in China, comprising 27 pilot cities (treatment group) and 21 non-pilot cities, to assess the carbon emission reduction benefits of low-carbon cities policies (control group). Table 1 depicts the distribution of pilot cities versus non-pilot cities. In the experimental group, there are eight pilot cities from the first round, of which three are located in pilot provinces from the first round. Also included are sixteen cities from the second list of pilot cities. The following 48 cities have equivalent levels of GDP, population, and industry structure. Due to the requirement of the DID method that the features of the two samples remain comparable, ten province capitals and eleven prefecture-level cities are chosen as the control group to ensure sample comparability.

Table 2 reports the descriptive statistics of variables. In these cities, the proportion of the third industry's value ranges from 28% to 72%, with an average of 45%. The average value percentage of the secondary industry is 47%, which is somewhat higher than the average value proportion of the third industry. The population size range in logarithmic terms is between 4.56 and 8.08 (unit of 10,000 people). The average wage of all citizens is around 10,69 yuan based on logarithms. The logarithmic range of fixed investment is between 14,000 and 18,24 (unit of 10,000) yuan. On a logarithmic scale, the average total retail sales of urban consumer products exceed 16 (unit of 10,000) yuan.

Table 2
Descriptive statistics of variables.

Variable	Symbol	Mean	S.D.	Min	Max
Carbon intensity	*CI*	1.566	0.919	0.317	5.814
Per capita gross domestic product	*Pergdp*	62,659	33,463	4731	156,000
The proportion of third industry output	*Third*	45.761	9.146	28.100	72.100
The proportion of second industry output	*Second*	47.827	7.715	25.700	64.500
Ln (population)	*Lnpop*	6.327	0.588	4.561	8.082
Ln (social average wage)	*Lnwage*	10.694	0.385	9.533	11.482
Ln (fixed investment)	*Lninvest*	16.817	0.883	14.001	18.241
Ln (total retail sales)	*Lnpcon*	16.358	0.989	13.660	18.243

Notes: There are 474 observations from our sample.

3.3. Methodology

3.3.1. The DID model

Using the DID model, this study investigates the impact of the LCPCP on urban carbon intensity. The DID model is the most used technique for estimating policy effect evaluations (Li et al., 2016; Tang et al., 2021b). The LCPCP is intended to reduce carbon intensity. This policy is a quasi-experimental shock to all pilot cities, producing an atmosphere conducive to assessing the policy's effects using the DID method. Treatment and control groups can be constructed based on the list of pilot cities, treatment and control groups can be constructed, and the DID model is used to analyze the differences in urban carbon intensity levels between the two groups before and after the LCPCP. The fundamental equation for regression takes the form:

$$CI_{i,t} = \alpha + \beta time_{i,t} \times treat_i + \lambda X + \gamma_t + \mu_i + \varepsilon_{i,t} \tag{2}$$

where $CI_{i,t}$is the urban carbon intensity. The first round of pilot cities, which began to be regulated in August 2010, *time* is 1 for years after 2011. The second list of pilot cities that started the low carbon regulation in November 2012 *time* is 1 for years after 2013; otherwise, it is 0. $treat_i$ It is 1 for the pilot city *i* at year *t*, and 0 for the control group. The coefficient of $time \times treat$ is the impact of China's LCPCP on carbon intensity, which is of interest in this paper. Since this strategy aims to reduce carbon emissions, we anticipate that this coefficient will be highly negative. *X* is the vector of control variables related to carbon intensity. γ_t is the year fixed effect, μ_i is the city fixed effect, and $\varepsilon_{i,t}$ is the random error.

3.3.2. Mechanism analysis model

To further validate the LCPCP mechanism, the following DID model is implemented:

$$M_{i,t} = \alpha + \beta time_{i,t} \times treat_i + \lambda X + \gamma_t + \mu_i + \varepsilon_{i,t} \tag{3}$$

where $M_{i,t}$ is mechanism variable. Other variables are similar to model (2). If the coefficient of $time \times treat$ is significant, the mechanism is verified.

4. Results and discussion

4.1. Main results

Table 3 displays the DID regression results. As indicated in column (1), the LCPCP significantly impacts carbon intensity at the city level. The interaction term coefficient is negative, indicating that the carbon intensity of pilot cities has decreased by 12.9% due to strict local government regulation of carbon emissions, thus proving *Hypothesis 1*. Our results support the conclusions reached by Yu

Table 3
Overall effect of the LCPCP on carbon intensity.

Variables	(1) All pilot cities	(2) First-round	(3) Second-round
Time*treat	−0.129***	−0.217***	−0.103**
	(−3.26)	(−3.88)	(−2.55)
Pergdp	0.00000463***	0.00000549***	0.00000494***
	(3.83)	(3.71)	(4.12)
Third	0.0118	0.0435**	0.0160
	(0.89)	(2.11)	(1.40)
Second	0.00304	0.0403**	−0.00404
	(0.25)	(2.06)	(−0.40)
Lnpop	0.616**	0.415	0.501*
	(2.49)	(1.62)	(1.92)
Lnwage	−1.058***	−1.598***	−0.441**
	(−4.58)	(−5.52)	(−2.11)
Lninvest	−0.376***	−0.476***	−0.306***
	(−6.38)	(−6.43)	(−4.59)
Lnpcon	−0.0513	−0.190	0.0908
	(−0.33)	(−1.05)	(0.64)
Year FE	Yes	Yes	Yes
City FE	Yes	Yes	Yes
Constant	14.85***	21.61***	5.427*
	(4.29)	(5.71)	(1.72)
N	474	317	367
R-squared	0.9399	0.9373	0.9531

Note: *t* statistics in parentheses.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

and Zhang (2021), Huo et al. (2022), and Liu (2023) that the LCPCP is successful in lowering carbon emissions.

We approximate the DID for each sampled city in column (1). We further separate the pilot policy into two phases to examine the effects of the policy based on the two-phase entry of different cities into the LCPCP. We use the 11 cities in column (2) as the treatment group and the 21 cities in column (3) as the control group. Column (3) displays the results using the 16 cities from the second round as the treatment group. According to the interaction coefficients, the carbon regulation campaign reduced the carbon intensity of the first- and second-round pilot cities by 21.7% and 10.3%, respectively. The longer duration of the first stage's regulation may account for the stronger policy impact of carbon reduction in the first stage compared to the second stage.

4.2. Pre-trend analysis

Before introducing the pilot strategy, the carbon intensity in both the treatment and control groups must display a parallel pattern for the DID estimate to be regarded as legitimate. We employ model (4) to verify the validity of the parallel trend hypothesis. The β_i coefficients' regression results are presented in Table 4. All estimated coefficients for the time period preceding the implementation of the policy are near zero, showing that the trend of carbon intensity levels between the two groups remains parallel. Using this conclusion, the research examines the parallel consumption tendency.

$$Y_{i,t} = \alpha + \beta_i \sum_{i}^{-6,-1} D^i \times Treat_{i,t} + \lambda X + \gamma_t + \mu_i + \varepsilon_{i,t} \tag{4}$$

Table 4
Pre-parallel test results.

Variables	(1) Carbon intensity
Pre_6	0.0121
	(0.12)
Pre_4	0.0808
	(0.87)
Pre_3	0.0950
	(1.19)
Pre_2	0.0715
	(0.77)
Pre_1	0.0677
	(0.75)
Controls	Yes
Year FE	Yes
City FE	Yes
_cons	14.11***
	(4.32)
N	474
R-squared	0.9395

Note: t statistics in parentheses.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

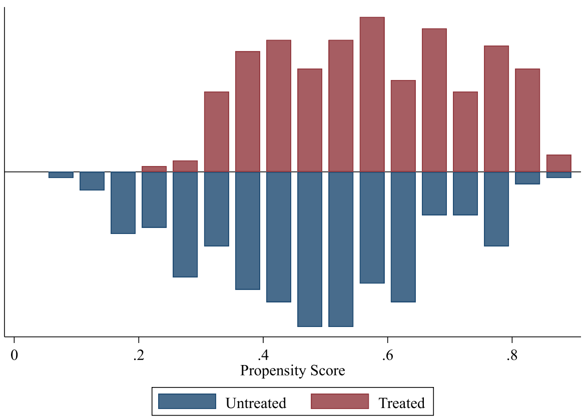

Fig. 1. Propensity score distributions.

4.3. Robustness test

The main result is that China's LCPCP decreased urban carbon intensity. In this section, we conduct four tests to validate the validity of our empirical strategy, including the PSM-DID identification method, the construction of a placebo test, and the changing of the dependent variable and sample.

First, to avoid sample selection bias, we use the PSM and DID model to choose a control group with characteristics similar to those

Table 5
The PSM quality test results.

Variable	Unmatched/ Matched	Mean Treated	Control	%bias	%reduct |bias|	T-test T	P>|t|
Pergdp	U	66,050	58,396	23.3		2.49	0.013
	M	62,820	64,843	−6.1	73.6	−0.65	0.516
Third	U	48.156	42.751	62.6		6.68	0
	M	45.758	46.459	−8.1	87	−0.96	0.336
Second	U	46.249	49.81	−47.9		−5.12	0
	M	48.176	47.99	2.5	94.8	0.29	0.773
Lnpop	U	6.3934	6.2428	26.1		2.79	0.005
	M	6.3253	6.3566	−5.4	79.2	−0.64	0.523
Lnwage	U	10.764	10.606	42		4.55	0
	M	10.711	10.704	1.9	95.4	0.21	0.837
Lninvest	U	16.906	16.705	23.1		2.48	0.014
	M	16.845	16.902	−6.5	72	−0.71	0.479
Lnpcon	U	16.508	16.169	35.2		3.76	0
	M	16.368	16.473	−11	68.8	−1.24	0.217

Table 6
Robustness tests results.

Variables	(1) PSM-DID method Carbon intensity	(2) Placebo test Carbon intensity	(3) Change dependent variable Ln (Carbon intensity)	(4) Change the sample Carbon intensity
Time*treat	−0.135***		−0.0373***	−0.125***
	(−3.21)		(−2.69)	(−2.70)
Placebo Time*treat		−0.0425		
		(−0.97)		
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
_cons	17.00***	14.17***	6.174***	16.39***
	(4.15)	(2.90)	(5.08)	(4.29)
N	437	283	474	387
R-squared	0.9347	0.9661	0.9802	0.9342

Note: *t* statistics in parentheses.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

Table 7
Regional heterogeneity analysis.

Variables	(1) The higher proportion of the secondary industry carbon	(2) The lower proportion of the secondary industry carbon
Time*treat	−0.0558	−0.201***
	(−1.16)	(−2.87)
Controls	Yes	Yes
Year FE	Yes	Yes
City FE	Yes	Yes
_cons	2.682	22.21***
	(0.72)	(3.33)
N	239	235
R-squared	0.9548	0.9332

Note: *t* statistics in parentheses.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

of the treatment group. Fig. 1 displays the distribution of carbon intensity propensity scores for the treatment and control groups. Multiple cities in the sample did not satisfy the assumption of common support.

This study emphasizes the standard deviation and the T-test for the conditional independence hypothesis. The matching effect improves as the absolute value of the standard deviation decreases. The T-test confirms if the mean values of the pilot and non-pilot cities are the same before and after matching; a T-value that is not statistically significant indicates a successful match. Table 5 displays the outcomes. The standard deviations of all variables are roughly 10%, and the T-values for the majority of variables are not statistically significant, indicating that the characteristics of the matched variables in the two groups have converged and meet the criteria for comparability. The outcome of the matched regression is presented in column (1) of Table 6. The coefficient of the interaction term remains highly negative, reinforcing our conclusion's validity.

Second, we construct a placebo test by assuming that the LCPCP was adopted in the first round in 2010 and implemented in the second round in 2012. To evaluate whether the decrease in carbon intensity existed prior to the implementation of the pilot policy, the DID model is run without the 2013 sample. As seen in column (2), the regression result is no longer statistically significant, showing that the LCPCP's low-carbon pilot campaign caused the reduction in carbon intensity.

Third, to prevent outliers from distorting the results and to further test the robustness of our results, we use the logarithmic value of carbon intensity instead of carbon intensity as the dependent variable. The interaction term's coefficient is also significantly negative, as seen in column (3).

Finally, we analyise the possible impact of the carbon emission trading scheme and the four municipalities directly administered by the central government (Feng et al., 2021). The sample excludes Beijing, Shanghai, Tianjin, Chongqing, Guangzhou, Shenzhen, Zhuhai, Wuhan, and Xianning. The result is still significantly negative, demonstrating that the benchmark conclusions achieved in this study are extremely robust independent of the regression model's sample sizes.

4.4. Heterogeneity analysis

To further analyze the heterogeneous effects of the policy, we divide the data into two groups depending on the urban heterogeneity of secondary industry proportion. As shown in Table 7, the coefficient of $Treat \times time$ in column (2) is significantly positive at the 1% level, whereas the coefficient of $Treat \times time$ in column (1) is no longer statistically significant. This shows that the LCPCP used in administrative orders to reduce carbon emissions is feasible and effective in locations with a relatively low proportion of secondary industries. It is difficult for the LCPCP to encourage carbon emission reduction in regions with a relatively large proportion of secondary industry. Thus, *Hypothesis 2* is verified and is similar to the findings of Lee et al. (2022), Wen et al. (2022), Pan et al. (2022) and Liu (2023), that also identify the heterogeneity of the LCPCP. This study makes the case that regional economic development is path-dependent (Isaksen, 2014) and that regions with a high percentage of secondary industry find it challenging to quickly change their industrial structure, which is known to be the main contributor to greater carbon emissions. Because secondary sectors make up a large amount of an area's economy, the LCPCP are ineffective there.

4.5. Mechanism analysis

Firms in pilot cities may have two options for lowering carbon emissions in response to the environmental stress induced by the LCPCP. The first option is to reduce production, which may be detrimental to the company's long-term growth and competitive advantage (Tang et al., 2021b). The second objective is to minimize carbon emissions per production unit through technological innovation, a more sustainable strategy for reducing emissions than in the past (Caparrós et al., 2013).

Using model (3), we examine the impact of the LCPCP on urban technological innovation. Using a dataset of city-level inventions consisting of three types of patents, Table 8 displays the regression results. According to column (1) of Table 8, the coefficient of $Treat \times time$ is considerably positive at the 10% level, signifying that the total number of patents acquired by the pilot cities has increased. The coefficients of $Treat \times time$ in columns (2) and (3) are much greater than 10% for specific types of patents, specifically invention patents, utility model patents, and design patents. The design patent is displayed in column (4). These results suggest that, as a result of the low carbon regulation initiative, the pilot cities have increased the quantity and quality of their technological innovations. Since technology innovation promotes emission reduction, technological development is a key mechanism for reducing carbon intensity in low-carbon pilot cities. Our conclusion is similar to Yang et al. (2023) which finds that the LCPCP can lower corporate pollution emissions by fostering technological innovation.

Additionally, this study divides the sample into two groups based on the geographical diversity of the regions. China's economic zones are traditionally divided into eastern and central-western areas (Song et al., 2013). Since eastern China is a moderately developed coastal region with regular international trade and exchanges, it is more developed than central and western regions, more dependent on natural resources, and further from the center of economic development. In addition, the eastern region has established public initiatives and environmental protection measures. However, in central and western China, enforcement of environmental standards is relatively low. With less mandatory environmental risk control requirements, there is a low opportunity cost for local firms to disregard their environmental responsibilities. Consequently, companies in eastern regions are more motivated to assume environmental responsibilities and develop innovative technology.

In conclusion, compared to the central and western regions, the eastern region has a more evolved legal system, sound rules, and robust enforcement of environmental management. A favorable institutional environment is conducive to effective external regulatory systems and open information disclosure (Julian and Ofori-Dankwa, 2013). These settings promote technological innovation and environmental awareness among firms. The coefficient of $Treat \times time$ in columns (1)-(3) of Table 9 is statistically positive, whereas the

Table 8
Mechanism of technology innovation.

Variables	(1) Total	(2) Invention	(3) Utility	(4) Design
Time*treat	2085.0*	612.3***	1781.7***	−184.7
	(1.97)	(2.90)	(3.39)	(−0.35)
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
_cons	225,260.9**	98,923.7***	107,895.0**	−12,540.7
	(2.42)	(5.35)	(2.34)	(−0.27)
N	474	474	474	474
R-squared	0.8462	0.8732	0.8384	0.7318

Note: *t* statistics in parentheses.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

Table 9
Geographical heterogeneity of technology innovation channel.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Eastern areas in China				Western and central areas in China			
	Total	Invention	Utility	Design	Total	Invention	Utility	Design
Time*treat	3513.9**	858.3***	3109.3***	−200.8	−1313.2	−244.1	−746.4	−322.6
	(2.08)	(2.60)	(4.09)	(−0.22)	(−1.37)	(−1.58)	(−1.31)	(−0.76)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	561,436.0***	215,269.1***	326,605.3***	−46,533.8	−172,139.5**	−5765.9	−93,005.4**	−73,399.5**
	(3.10)	(6.09)	(4.00)	(−0.48)	(−2.52)	(−0.52)	(−2.28)	(−2.41)
N	258	258	258	258	216	216	216	216
R-squared	0.8587	0.9010	0.8744	0.7091	0.8074	0.8241	0.7761	0.7191

Note: *t* statistics in parentheses.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

coefficient of $Treat \times time$ in columns (5)-(7) is no longer significant. This demonstrates that the eastern region places a greater focus on technological innovation support than the central-western region.

5. Conclusion and policy implications

In light of the climate change challenge, an increasing number of countries are concentrating on the harmony between economic growth, climate change mitigation, and carbon emission reduction. The LCPCP is a massive initiative in China, and its execution could aid in reducing global climate change and altering economic distribution (Zhu and Lee, 2022). Therefore, this study investigates the underlying mechanisms at play and the effectiveness of this strategy in reducing urban carbon intensity.

In order to ascertain how China's LCPCP affects urban carbon intensity, this study uses the program as a quasi-natural experiment and analyses this with the DID model. Specifically, using panel data from 2007 to 2017 in China, we compare the changes in carbon intensity between pilot cities affected by decarbonization programs and unaffected cities and discover that the campaign caused a sizable decrease in carbon intensity in the pilot cities. According to heterogeneity analysis, the LCPCP was more common in areas with a lower percentage of secondary industries. Our results imply that the decarbonization effort, particularly in eastern China, may be able to reduce carbon intensity by encouraging local technological innovation.

Our study offers policy implications for the Chinese government and other governments to construct environmental regulatory legislation and advance the national low-carbon development pathway based on the above findings.

(1) To promote low-carbon growth, the Chinese government should broaden the scope of LCPCP. This study shows that the implementation of LCPCP led to a sizable reduction in carbon intensity, demonstrating that the implementation of LCPCP resolves the issue of environmental policy implementation deviance. The government should enhance regional communication, enhance pertinent supporting policies, and maximize the policy impact of the LCPCP to encourage green development by studying and promoting the successful experience of pertinent pilot regions. Policymakers can help China achieve its "30•60 double carbon objective" at the urban level by compiling pilot experience and creating typical cases, which will further push and speed up the building of the LCPCP.

(2) Promote LCPCP in line with local conditions or specific industry. In other words, while drafting climate policies, it is best to take the heterogeneity caused by urban characteristics into account. Market-oriented policies could be used in these locations to optimize the industrial structure in light of the failure of decarbonization strategies in regions with a dominant secondary sector. This initiative encouraged innovative behavior to boost carbon reduction. As a result, the low-carbon strategy might be supported in conjunction with policies that encourage technical innovation and industry reorganization, yielding larger emission reduction effects.
(3) The government should encourage enterprises to hasten the development of green technology because the decarbonization campaign can lower carbon intensity by fostering technical innovation at the local level. Particularly, there should be a detailed and explicit LCPCP. In order to advance technological innovation together, local governments should be encouraged to attract high-tech FDI and to promote and benefit from the superior environmental protection technology and management experience of foreign enterprises.

CRediT authorship contribution statement

Yi-Shuai Ren: Conceptualization, Formal analysis, Project administration, Methodology, Data curation, Software, Writing – original draft, Writing – review & editing, Funding acquisition. **Pei-Zhi Liu:** Conceptualization, Formal analysis, Methodology, Software, Writing – original draft. **Tony Klein:** Conceptualization, Validation, Project administration, Writing – original draft, Writing – review & editing. **Lisa Sheenan:** Conceptualization, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data availability

Data will be made available on request.

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