# Has the construction of National Independent Innovation Demonstration Zones reduced the urban carbon emissions? A quasi-natural experiment in China

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**Research Article**

**Keywords:** National Independent Innovation Demonstration Zones, Carbon emission reduction, Difference-in-differences, Innovation-driven development

**Posted Date:** April 26th, 2022

**DOI:** https://doi.org/10.21203/rs.3.rs-1520158/v1

# Abstract

This paper investigates the effects of innovation-driven development on carbon emissions reduction in Chinese urban area. We use panel data on 285 cities which covers 95.96% of Chinese cities during the period of 2003 to 2017. The time-varying difference-in-differences (DID) model is employed to estimate the impact of the creation of China's National Independent Innovation Demonstration Zones (NIDZs) on urban carbon emission levels. Compared with non-pilot cities, our results indicate that total carbon dioxide emissions and emission intensity of pilot cities decreased by 4.8% and 5.8% respectively. The results suggest that the construction of NIDZs can significantly promote urban carbon emission reductions. Moreover, our mechanism tests indicate that this pilot policy can encourage technological innovation and optimize industrial structure, which in turn suppresses urban carbon dioxide emissions. Furthermore, heterogeneity analysis shows that the policy effect is stronger in cities with higher levels of human capital, government finance and information infrastructure. Overall, this study enriches the relevant research on carbon emission reduction of cities and puts forward some policy recommendations.


# 1. Introduction

As well known, global warming is increasingly affecting the survival and development of human beings (Dahlmann et al., 2019; Bai et al., 2019; Liu et al., 2021), and carbon dioxide is recognized as the main contributor that exacerbates the greenhouse effect (Gehrsitz, 2017; Dong et al., 2018; Le et al., 2020). For this reason, the Chinese government focuses on carbon emissions reduction, and during the 2009 Copenhagen Summit, China pledged to achieve a 40–45% reduction in the level of carbon dioxide emission per unit of GDP by 2020 compared with 2005. Since then, China's carbon reduction targets have been pursued at a higher level, representing a long-term and sustained effort. In September 2020, at the 75th session of the United Nations General Assembly, China promised to reach "carbon peak and neutrality goals" by 2030 and 2060 respectively. Against this background, the Chinese government has actively implemented different kinds of policies aiming to reduce carbon dioxide emissions (Liao et al., 2021), such as building low-carbon cities, establishing and developing a carbon emissions trading market, incorporating environmental improvement into the performance assessment of officials, and so on. Whether such government-led policies can promote carbon emission reduction is a matter of great concern to policy makers and scholars.

The established literature has explored many factors influencing carbon dioxide emissions from several perspectives, including international trade (Rhee and Chung, 2006; Ang, 2009; Saud et al., 2018), government decentralization (Middlemiss and Parrish, 2010), economic agglomeration (Yu et al., 2020), urbanization (Poumanyvong and Kaneko, 2010; Martínez-Zarzoso and Maruotti, 2011; Cai et al., 2021), and economic growth (Alshehry and Belloumi, 2015; Cohen et al., 2018; Li and Wang, 2019). Additionally, efforts to find an efficient and rational path to carbon emission reduction through scientific and technological innovation has received increasing attention (Li et al., 2017). Meanwhile, environment-related policies have a significant effect in bringing about carbon emission reductions (Friedl and Getzner, 2003), and governments are playing an increasingly important role (Baboukardos, 2017). For example, the low-carbon city pilot policy is an important measure to achieve low-carbon transformational development. Existing empirical studies have found that the construction of low-carbon cities is generally beneficial to reducing carbon dioxide emissions (Wolff et al., 2014; Gehrsitz, 2017; Pei et al., 2019; Wang and Wei, 2020; Yu and Zhang, 2021). In addition, carbon emission trading schemes are not only a market instrument to reduce and control carbon dioxide emissions using market mechanisms, but are also an institutional innovation and policy tool to implement the national carbon peak target and carbon-neutral vision (Hoffmann, 2007; Anger, 2010; Calel and Dechezleprêtre, 2016; Nguyen et al., 2019; Zhou et al., 2019; Dong et al., 2019; Zhang and Zhang, 2020).

In recent years, China has actively carried out pilot work in creating NIDZs, aiming to further implement an innovation-driven development strategy, improve the institutional mechanism of science and technology innovation (Gao et al., 2015). As a frontier of technology innovation cooperation and a comprehensive carrier to promote regional innovation development, NIDZs improve the innovation capability of enterprises in the region and promote technological progress and industrial structure upgrading through policy incentives, resource inclination, and strategic leadership (Huang et al., 2013). Furthermore, NIDZs can spur the rapid development of cities, thus serving as an important mechanism to accelerate innovation development in the new era (Wang and Ma, 2019).

Ample studies have been conducted in policy development process, regional differences, and strategic positioning of NIDZs at the theoretical level. They have explored various aspects of how to keep pace with time and continuously improve NIDZ development while summarizing the achievements already made. These researches are particularly rich in macroscopic frameworks including operation mechanism, system supply, and functional positioning, such as the studies made by Huang et al. (2013) and Gao et al. (2015). However, few studies have analysed the policy effects of the pilot NIDZ creation at the practical level. Existing research is limited to studies of its impact on the innovation level (Wang and Ma, 2019) and does not broaden the scope of its usefulness. The gaps in the literature provide the scope for this study.

The main goals of establishing NIDZs are “strengthening environmental protection”, “developing new energy industries and high-tech industries”, “establishing energy-saving and environmental protection industry clusters”, and “building a ‘green, low-carbon and recyclable’ ecological system”. It can be seen that low-carbon innovation and pollution reduction are the central principles and objectives of NIDZ construction, so we take them as the starting point to investigate whether the construction of NIDZs has significantly reduced carbon emissions in the host city. If so, through which mechanisms does this effect occur? Is there heterogeneity in carbon reduction effects depending on city characteristics? The answers to these questions are not only important for consolidating the previous achievements of the NIDZs and broadening their development space in the future, but also for providing useful policy insights for China to achieve its “carbon peak and neutrality goals”.

China provides a nice context for studying these issues. Firstly, China has become the world's largest carbon dioxide emitter since 2006 (Zheng and Kahn, 2017; Cheng et al., 2019), and the contradiction between economic development and environmental protection has become increasingly acute (Chen et al., 2021). Against this background, the proposed target of carbon emission reduction presents both a challenge and an opportunity for China to reshape and upgrade its economy. Accordingly, establishing reasonable and effective carbon emission reduction policies is particularly crucial. Secondly, China clearly emphasizes the need to implement a coordinated regional development strategy. As a typical location-oriented policy, the significance of the construction of NIDZs has gone beyond the specific NIDZ sites themselves, so it is necessary to explore the policy effects in depth. In addition, because the pilot areas are designated by the central government, they have the property of "top-down" development, thus providing a valuable and convincing quasi-natural experimental sample for policy evaluation (Hu et al., 2020).

This paper contributes to the literature in the following three aspects. First, in terms of research perspective, based on the policy experiment of NIDZ construction, this study systematically investigates the carbon reduction effect of innovation-driven development. This paper is one of the early research paper to explore the impact of the pilot policy of NIDZ creation on carbon dioxide emissions in Chinese cities. Because low-carbon-oriented economy is an important principle of NIDZ construction, the assessment of the effect of this policy is indispensable. Secondly, in terms of practical implications, this paper finds the impact mechanism of NIDZ construction on carbon emission reduction from the perspective of technological progress and industrial upgrading, which enriches the existing literature. Lastly, in terms of empirical methods, this paper is based on the time-varying DID model, using the quasi-natural experiment of the NIDZ construction to effectively mitigate the endogeneity problem.

The rest of the paper is organized as follows: Section 2 describes the policy background and theoretical analysis, Section 3 discusses the research design, Section 4 presents the empirical results including benchmark regression analysis and robustness tests, Sections 5 and 6 provide the mechanism and heterogeneity analysis, and Section 7 concludes the article with policy implications.

## 2. Policy Background And Theoretical Analysis

# 2.1 Policy Background

Innovation is an important pathway for promoting industrial transformation and achieving sustainable economic development (Uyarra et al., 2020; Du et al., 2021). Accordingly, the Chinese government has focused on improving the national innovation system and gradually carried out pilot work on the construction of NIDZs in order to explore the path of innovation with Chinese characteristics and identify effective laws and practices of innovation-driven development.

Specifically, NIDZs are regions approved by the State Council of China to serve as demonstrations in promoting innovation-driven development and transforming the mode of economic development; NIDZs aim to continuously improve the institutional mechanism of technological innovation and play an important role of radiation. From March 2009, when Zhongguancun in Beijing was approved as the first NIDZ, up to the approval of the Poyang Lake NIDZ in August 2019, China has approved 21 NIDZs in 56 cities successively (See Appendix A). This effort has required the promulgation and implementation of wide-ranging policies to design and plan the development goals and key tasks for these NIDZs, guaranteeing that the pilot project can be implemented in a scientific and orderly manner. This demonstrates China's determination to actively enhance the level of innovation and improve the quality of economic development.

Of the 285 cities with pilot NIDZs during the research period and sample used in this paper, the number of pilot cities is 42, accounting for 14.7%. Although NIDZs can be found throughout the country, personalized innovation development has become a distinctive feature of each NIDZ. The construction of NIDZs has become an inevitable requirement for accelerating regional and national innovation development, and an important step to realize China's position among the forefront of innovative countries.

## 2.2 Theoretical analysis

Many scholars have studied the factors affecting urban carbon dioxide emissions from different perspectives, and a lack of technological innovation and unreasonable industrial structure are important reasons behind China becoming the world's largest carbon dioxide emitter (Ang, 2009; Li and Wang, 2019). Although the level of innovation in China has been increasing, improving the quality of China's economic development, there is still an innovation gap compared with developed countries (Ouyang et al., 2020), especially in terms of green and low-carbon technologies (Gao and Yuan, 2021). Technological innovation has a spillover effect, which is conducive to driving high-quality economic development. Moreover, industrial structure in China has been optimized in recent years, but the industrial sector, which is the main source of carbon emissions, remains the core of economic development (Hammoudeh et al., 2014; Bel and Joseph, 2015; Shan et al., 2016). A strong correlation effect exists between total carbon emissions and industrial restructuring (Jotzo and Loěschel, 2014; Li et al., 2017; Zhang et al., 2020). Therefore, enhancing the level of technological innovation and promoting industrial structure upgrading are critical to reduce carbon dioxide emissions (Du et al., 2021), which are also important perspectives that this paper believes the construction of the NIDZs will play a role.

First, NIDZ will reduce urban carbon dioxide emissions by improving technological innovation. Official documents state that absorbing innovative talents and increasing innovation investment are important considerations motivating the creation of NIDZs. The pilot cities actively recruit overseas high-level professional, technical, and business management talents, thereby supporting innovation factors such as talent, technology, capital, and information to agglomerate in the NIDZs. Therefore, pilot cities exhibited enhanced innovation levels. Regarding the channels through which technological innovation affects urban carbon emissions, on the one hand, low-carbon technology research is an important dimension of technological innovation, and an overall improvement in the level of technological innovation drives the continuous progress of low-carbon technology (Wang and Qiu, 2021). This accelerates the use and development of low-carbon technology at the level of market and demand, which in turn drives reduction in carbon emissions (Li et al., 2017); On the other hand, improving the level of technological innovation contributes to the application and promotion of energy-saving and emission-reduction technologies (Du and Li, 2019; Zheng and Li, 2020), encouraging the adoption of new technologies and low-carbon operations in industries with high emissions and high energy consumption, which makes energy use more efficient and thus lowers carbon emissions (Hu et al., 2020).

Secondly, NIDZs offer a route to reduce urban carbon dioxide emissions by driving industrial structure optimization and upgrading. The relevant policy documents require pilot cities to overcome institutional barriers to the organic integration of innovation resources based on the market allocation of resources (Wang and Ma, 2019). In addition, pilot cities are also required to vigorously develop high-tech industries, knowledge-intensive service industries, and so on. Meanwhile, drawing on active promotion from national policies, local governments should strongly support the construction and development of R&D centers of large domestic and foreign enterprises and provide financial support for enterprises structural adjustment and technological transformation. These actions will significantly optimize the industrial institutions in the pilot cities. At the same time, low-energy-consumption and low-emission industries are further emphasized, whereas high-energy-consumption and high-pollution industries are reasonably controlled (Hong et al., 2021). Low-carbon tertiary industries including modern service industries are developed, and the traditional sloppy development mode is transformed. This promotes the energy-saving, efficient, and sustainable development of the city, which in turn reduces its level of carbon dioxide emissions (Huang et al., 2020).

In response to the above analysis, the following two hypotheses are proposed in this paper:

**Hypothesis 1**

Construction of NIDZs will help reduce carbon dioxide emission levels in cities.

**Hypothesis 2**

Construction of NIDZs curbs urban carbon dioxide emissions by promoting technological innovation and optimizing the industrial structure.

## 3. Study Design

# 3.1 Time-varying DID model

This paper follows studies such as Wolff (2014), Li et al. (2016), Gehrsitz(2017), Cheng et al. (2019) and others in identifying the impact of NIDZ creation on urban carbon dioxide emissions using the time-varying DID method with the following econometric model:

$$Y_{it} = \alpha + \beta treat_{it} + \gamma X_{it} + u_i + \lambda_t + \varepsilon_{it}$$

where $i$ and $t$ denote different cities and years, respectively; $Y_{it}$ denotes the carbon emission level of city $i$ in year $t$, measured by two indicators (total carbon emissions and carbon emission intensity); $treat_{it}$ denotes the dummy variable of the pilot; $X_{it}$ denotes the control variables selected in this paper; $u_i$ denotes the city fixed effects; $\lambda_t$ denotes the year fixed effects; $\varepsilon_{it}$ denotes the random error term, clustered to city and year levels. $\beta$ measures the net effect of the NIDZ pilot projects on urban carbon emissions, making it the core coefficient of most interest in this paper. If $\beta$ is less than zero and significant, it indicates that the NIDZs pilot projects have significantly reduced the carbon emissions in their host cities, which verifies Hypothesis 1.

# 3.2 Sample selection and data sources

In this paper, cities that established a NIDZ during the period under examination are considered the experimental group, whereas cities that did not establish a NIDZ are considered the control group. The time-varying DID method is used to test the carbon-reduction effect of NIDZ establishment on cities. In addition to considering data availability, this paper also controls for the heterogeneity of domestic and international environments, and finally uses panel data of 285 cities in China covering the period of 2003–2017 as the study sample.

For the variables studied in this paper, data on city carbon dioxide emissions are gotten from China Emission Accounts and Datasets (CEADs), data on city comprehensive innovation indexes are obtained from the China City and Industry Innovation Report, and data on other variables are gotten from official statistics such as the China City Yearbook, China City Construction Statistical Yearbook, and the China Statistical Yearbook. Meanwhile, in order to eliminate the interference of inflation factors and make the data fully comparable, all nominal indicators were adjusted to constant prices based on the corresponding price indices of each city in each year, with 2003 as the base period. In addition, missing data are interpolated to obtain balanced panel data.

# 3.3 Variable selection and measurement

# 3.3.1 Explained variables

Total urban carbon dioxide emissions (*lncar*) and carbon dioxide emission intensity (*lnpcar*) are the explained variables in this paper. Total urban carbon dioxide emissions are expressed as the logarithm of automobile emissions in each city, and urban carbon dioxide emissions intensity is expressed as the logarithm of the ratio of carbon dioxide emissions to real GDP in each city.

# 3.3.2 Core explanatory variable

The core explanatory variable in this paper is the creation of NIDZs (*treat*), which is equal to 1 for a city in the year of implementation of this pilot policy and each subsequent year, and 0 otherwise. In defining the year of a NIDZ's creation, it is taken into account that in some years, the policy is implemented later in the year and so the impact on the city in that year of creation will be weaker. In this paper, we use the year of creation as the starting year of the policy implementation for the city if the NIDZ was established from January to September, and take the following year as the starting year if the NIDZ was established from October to December. Meanwhile, the year of policy enactment as the year of pilot shock is added to the robustness test.

### 3.3.3 Control variables

In order to control for the effects of other variables on urban carbon emissions, additional control variables were selected in the regression analysis: real GDP per capita (*lnrgdp*), energy intensity (*lnene*), population density (*lnpd*), share of secondary industry (*sind*), share of science and technology expenditure (*sci*), and financial development level (*finc*). Real GDP per capita is expressed as the logarithm of the ratio of real GDP to total population at the end of the year in each city. Energy consumption intensity is expressed as the logarithm of the ratio of electricity consumption to real GDP in each city. Population density is expressed as the logarithm of the ratio of total population to land area in the administrative area at the end of the year in each city. The share of secondary industry is expressed as the proportion of the value added of secondary industry to GDP. Similarly, the share of science and technology expenditure is expressed as the proportion of budgetary expenditures on science and technology to budgetary fiscal expenditure. The level of financial development is expressed as the proportion of the loan balances of financial institutions to GDP. The descriptive statistics of the above variables is presented in Table 1.

Table 1
Descriptive statistics of variables

| Variables | Mean | SD | Min | Median | Max |
|---|---|---|---|---|---|
| *lncar* | 16.703 | 0.817 | 14.240 | 16.714 | 19.257 |
| *lnpcar* | 0.999 | 0.597 | -1.208 | 0.957 | 3.445 |
| *treat* | 0.029 | 0.168 | 0.000 | 0.000 | 1.000 |
| *lnrgdp* | 9.849 | 0.821 | 7.545 | 9.824 | 12.563 |
| *lnene* | 1.714 | 0.822 | -2.372 | 1.691 | 5.539 |
| *lnpd* | 1.116 | 0.914 | -3.053 | 1.257 | 4.355 |
| *sind* | 48.343 | 10.985 | 14.950 | 48.640 | 90.970 |
| *sci* | 0.012 | 0.015 | 0.000 | 0.007 | 0.290 |
| *finc* | 1.304 | 0.710 | 0.245 | 1.114 | 9.950 |

## 4. Empirical Analysis

### 4.1 Baseline regression analysis

In order to assess the impact of the pilot NIDZ creation on urban carbon emissions, this paper regresses model (1) and the results are shown in Table 2. It is easy to find that, after controlling for city fixed effects and time fixed effects, the coefficients of the policy pilot dummy variable$\beta$are significantly negative at the 1% confidence level, regardless of whether the model includes control variables or not. This indicates that the pilot NIDZ creation generally helps to reduce urban carbon emissions, which confirms hypothesis 1.

Regarding the core explanatory variables and control variables, this paper explains them with the partial estimation results in columns (2) and (4) of Table 2. Given other conditions constant, total carbon dioxide emissions and emission intensity of pilot cities decreased by 6.3% and 10.2% respectively compared to the non-pilot cities. The pilot NIDZ creation significantly suppresses urban carbon dioxide emissions. For the regression results of control variables, real GDP per capita is positively correlated with total carbon emissions but negatively correlated with carbon emissions intensity. The estimated coefficient of population density is both positive at the 1% confidence level, indicating that the degree of population concentration exacerbates the level of carbon emissions. The estimated coefficient of the share of secondary industry in column (2) is significantly positive, showing that an increase in the share of secondary industry increases urban total carbon dioxide emissions. The estimated coefficient of the share of science and technology expenditure is significantly negative, suggesting that an increase in the share of science and technology expenditure has a catalytic effect on the reduction of urban carbon emissions.

Table 2
Baseline regression results

| Variables | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | *lncar* | | *lnpcar* | |
| *treat* | -0.077*** | -0.048*** | -0.068*** | -0.058*** |
| | (0.011) | (0.010) | (0.009) | (0.010) |
| *lnrgdp* | | 0.267*** | | -0.139*** |
| | | (0.050) | | (0.037) |
| *lnene* | | 0.051*** | | 0.051*** |
| | | (0.005) | | (0.005) |
| *lnpd* | | 0.242** | | 0.108* |
| | | (0.108) | | (0.058) |
| *sind* | | 0.004*** | | 0.001*** |
| | | (0.000) | | (0.000) |
| *sci* | | -0.228 | | -0.662*** |
| | | (0.227) | | (0.253) |
| *finc* | | 0.002 | | 0.002 |
| | | (0.005) | | (0.004) |
| *Constant* | 16.705*** | 13.531*** | 1.001*** | 2.110*** |
| | (0.001) | (0.571) | (0.001) | (0.385) |
| *Control variables* | No | Yes | No | Yes |
| *City FE* | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes |
| *N* | 4,275 | 4,275 | 4,275 | 4,275 |
| $R^2$ | 0.987 | 0.989 | 0.980 | 0.981 |

Notes: ***, ** and * indicate statistical at 1%, 5% and 10% levels, respectively. Standard errors clustered at the city-year level are in parentheses.

## 4.2 Robustness test

### 4.2.1 Test of the parallel trend

This paper adopts the time-varying DID method to explore the impact of the pilot NIDZ creation on urban carbon emissions. An important prerequisite for the time-varying DID method to be usable is that if there is no policy shock, the trend of urban carbon emission levels of cities with NIDZs (experimental group) and cities without NIDZs (control group) have a common trend of change. They do not have systematic differences, or if there are differences, the differences are fixed. To test whether this precondition is satisfied, this paper refers to the literature of Gentzkow (2006), Beck et al. (2010), Moser and Voena (2012), Gehrsitz (2017), and uses the event analysis method to set up the following econometric model:

$$Y_{it} = \alpha + \sum_{-4 \leqslant k \leqslant 6,\, k \neq 0} \beta_k D_{it}^{k} + \gamma X_{it} + u_i + \lambda_t + \varepsilon_{it}$$

2

where $D_{it}^{k}$ denotes the dummy variable of the event of the creation of NIDZs. Assuming that the year when the city *i* establishes the NIDZ is $l_i$, *t* is the year, and we define $k = t - l_i$. When $k \leqslant -4$, $D_{it}^{-4}=1$, otherwise 0; when $-4<k<6$ and $k \ne 0$, $D_{it}^{k}=1$, otherwise 0; when $k \geqslant 6$, $D_{it}^{6}=1$, otherwise 0. Meanwhile, this paper takes the year when the NIDZ is established ($k=0$) as the base period, so this dummy variable ($D_{it}^{0}$) is not included in model (2). In addition, the other variables in model (2) are set consistently with the benchmark model (1).

In this paper, we focus on the parameters $\beta_k$, which reflect the impact of the pre-pilot and post-pilot on the carbon emission levels in different sample groups of cities. In order to visualize the dynamic impact of NIDZ creation on carbon emissions, the estimated values of the parameters $\beta_k$ in model (2) and their 95% confidence intervals are plotted, as shown in Fig. 1. The horizontal axis indicates the number of years before and after the pilot NIDZ creation, and the vertical axis indicates the changes of carbon emission levels in cities.

If the original hypothesis that the parameters $\beta_k$ are equal to zero cannot be rejected when $k<0$, the common trend hypothesis holds. According to the results in Fig. 1, it can be found that the estimated values of the parameters $\beta_k$ are not significantly different from zero before the construction of NIDZs, which suggests that there is no significant difference in the carbon emission levels between the experimental and control group cities before the policy pilot, and proves that the time-varying DID method in this paper satisfies the common trend hypothesis. Meanwhile, when $k>0$, the parameters $\beta_k$ measure the dynamic effect of the policy. It can be found that the estimated value of the parameters $\beta_k$ are always negative after the second year of the construction of NIDZs, no matter for the total amount of carbon dioxide emission or the emission intensity in city, which indicates that the carbon emission reduction effect of NIDZ creation exists and appears after the second year of the pilot. There is a time lag, probably related to the fact that it takes some time for technological upgrading and industrial transformation. Moreover, the trend shows that the inhibitory effect of the pilot policy on urban carbon dioxide emissions is not only continuous, but also has a tendency to strengthen continuously.

# 4.2.2 Placebo test

In order to further mitigate the possibility of omitted variables interfering with the effect of the NIDZs construction on urban carbon emission reductions, this paper refers to Chetty et al. (2009), Zhang and Zhang(2020), and randomly selects cities implementing the pilot to conduct a placebo test. Specifically, the paper randomly chooses the same number of cities as the experimental group according to the number of pilot cities that have launched the NIDZ each year, and constructs dummy variables $treat_{{it}}^{{false}}$ using the setting of the baseline model. The regressions were repeated 1000 and 2000 times using model (3).

$${Y_{it}}=\alpha +\beta treat_{{it}}^{{false}}+\gamma {X_{it}}+{u_i}+{\lambda _t}+{\varepsilon _{it}} \tag{3}$$

Any significant results after the simulations indicate that the baseline regression results of this paper are biased. Figure 2 and Fig. 3 plot the distribution of the regression coefficients of $treat_{{it}}^{{false}}$ and the corresponding p-values for the two simulations. It is easy to see that the distribution of the regression coefficients obtained based on random sample estimation is around 0 and conforms to a normal distribution. In contrast, the baseline regression coefficients in this paper (shown as vertical dashed lines on the left side of the figures) are smaller than the vast majority of the simulated values, which are obvious outliers. It can be further found that the probability of the baseline regression results occurring is less than 1%. These results indicate that the estimated results of the benchmark regression are a small probability event due to other factors that happen to get the benchmark regression. It can be concluded that the inhibitory effect of the construction of NIDZs on urban carbon emissions is not affected by the omitted variables, and the previous regression conclusions are robust.

### 4.2.3 Consider the impact of city attributes

The time-varying DID method is an important method for studying quasi-natural experiments, which is most desirable when the selection of experimental and control groups is randomized. If the determination of the list of pilot and non-pilot cities is random, the core explanatory variables (*treat*) in this paper satisfy the exogeneity requirement and thus the estimated coefficients satisfy unbiasedness. However, the determination of the list of pilot cities often does not strictly satisfy the randomness requirement, and is closely related to the inherent attributes of cities such as their economic development level, administrative rank, openness, and geographic location. The differences among cities caused by these attributes may also have different effects on the level of urban carbon emissions over time, which in turn makes the estimated results biased. The explanatory variables selected in this paper are not associated with the choice of pilot cities, which has somewhat mitigated the endogeneity problem. In order to assess the policy effects of the pilot of NIDZs construction more accurately, this paper refers to Edmonds et al. (2010), Li et al. (2016), controlling for five types of city attributes. Specifically, we add crossover items of city attributes and time trend polynomial to the benchmark regression model, mitigating the effect of selection. The specific econometric model is as follows:

$${Y_{it}}=\alpha +\beta trea{t_{it}}+{S_n} \cdot f(t)+\gamma {X_{it}}+{u_i}+{\lambda _t}+{\varepsilon _{it}}$$

where $S_n$ denotes city attributes. In this paper, five types of variables are selected as proxy variables reflecting city attributes, including whether the city is a provincial capital city, whether it is a sub-provincial city, whether it is a northern city, whether it is a special economic zone city and whether it is a large or medium-sized city, with yes being 1 and no being 0. $f(t)$ is a polynomial indicating the time trend, including the primary, secondary and tertiary terms of the time trend dummy variable. The effect of differences in the inherent attributes of cities among themselves over time on the level of urban carbon emissions is controlled for $S_n \cdot f(t)$. The problem of estimation bias caused by the non-random selection of pilot and non-pilot cities for the construction of NIDZs is mitigated to some extent. The regression results are presented in Table 3.

In columns (1) to (5), the dummy variables for city attributes are the five variables mentioned above respectively. In column (6), the dummy variables for these five types of city attributes are put into model (4). It can be found that the estimated coefficients of the pilot NIDZ creation in columns (1) to (6) are all significantly negative and pass the 1% statistical test, and the results are very close to the estimated value of $\beta$ in the baseline regression. This indicates that after taking into account the possible effects of differences in the inherent attributes of cities, the creation of NIDZs still has a significant inhibitory effect on urban carbon emissions, making the previous conclusions more robust.

Table 3
Consider the impact of city attributes

| **Variables** | **(1)** | **(2)** | **(3)** | **(4)** | **(5)** | **(6)** |
|---|---|---|---|---|---|---|
| Panel A: *lncar* | | | | | | |
| *treat* | -0.058*** | -0.038*** | -0.058*** | -0.048*** | -0.049*** | -0.050*** |
| | (0.011) | (0.011) | (0.011) | (0.010) | (0.011) | (0.011) |
| *Constant* | 13.493*** | 13.574*** | 13.861*** | 13.558*** | 13.530*** | 13.848*** |
| | (0.552) | (0.578) | (0.523) | (0.562) | (0.570) | (0.506) |
| {S_n} \cdot f(t) | Yes | Yes | Yes | Yes | Yes | Yes |
| *Control variables* | Yes | Yes | Yes | Yes | Yes | Yes |
| *City FE* | Yes | Yes | Yes | Yes | Yes | Yes |
| *Year FE* | Yes | Yes | Yes | Yes | Yes | Yes |
| *N* | 4,275 | 4,275 | 4,275 | 4,275 | 4,275 | 4,275 |
| {R^2} | 0.989 | 0.989 | 0.989 | 0.989 | 0.989 | 0.990 |
| Panel B: *lnpcar* | | | | | | |
| *treat* | -0.064*** | -0.046*** | -0.064*** | -0.056*** | -0.055*** | -0.051*** |
| | (0.010) | (0.010) | (0.010) | (0.010) | (0.010) | (0.010) |
| *Constant* | 2.086*** | 2.163*** | 2.305*** | 2.216*** | 2.113*** | 2.383*** |
| | (0.373) | (0.394) | (0.378) | (0.400) | (0.388) | (0.388) |
| {S_n} \cdot f(t) | Yes | Yes | Yes | Yes | Yes | Yes |
| *Control variables* | Yes | Yes | Yes | Yes | Yes | Yes |
| *City FE* | Yes | Yes | Yes | Yes | Yes | Yes |
| *Year FE* | Yes | Yes | Yes | Yes | Yes | Yes |
| *N* | 4,275 | 4,275 | 4,275 | 4,275 | 4,275 | 4,275 |
| {R^2} | 0.981 | 0.981 | 0.982 | 0.981 | 0.981 | 0.982 |
| Notes: ***, ** and * indicate statistical at 1%, 5% and 10% levels, respectively. Standard errors clustered at the city-year level are in parentheses. | | | | | | |

## 4.2.4 Consider the impact of other policies

The robustness tests conducted above further ensure the reliability of the baseline regression results. However, in the actual operation of real economic and social systems, the policies implemented at the city level are complex and diverse, making it inevitable that we will be influenced by other policies when considering the implementation effects of a particular policy (Chen et al., 2021). This will in turn bias our assessment of the effects of the target policy. Therefore, during the examination period of this study, based on the existing literature, two types of policy shocks that affect the level of urban carbon emissions are considered. These include low-carbon city pilot (*treat*1) and carbon emission trading pilot (*treat*2). The specific econometric model is set as follows:

$${Y_{it}}=\alpha +{\beta _1}trea{t_{it}}+{\beta _2}treat{1_{it}}+{\beta _3}treat{2_{it}}+\gamma {X_{it}}+{u_i}+{\lambda _t}+{\varepsilon _{it}} \tag{5}$$

For the two policy dummy variables, if city i implements the low-carbon city pilot policy in year t, then city i has $treat{1_{it}} = 1$ in year t and subsequent years, and 0 otherwise. Similarly, if city i implements the pilot carbon trading policy in year t, then city i has $treat{2_{it}}=1$ in year i and subsequent years, and 0 otherwise. The regression results are shown in Table 4.

It can be found that whether the dummy variables of low carbon pilot policy and carbon emission trading pilot policy are added alone or both are added to the regression, the inhibitory effect of NIDZ creation on the carbon dioxide emissions of the host city is still significant, so the previous conclusion still holds after taking into account other policy interferences. Meanwhile, after regression using model (5), the estimated coefficients of both low-carbon city pilot and carbon emission trading pilot are also found to be significantly negative, affirming the positive effects of these two policies on carbon emission reduction in cities, which is also consistent with conclusions of available literature(Pei et al., 2019; Nguyen et al., 2019).

Table 4
Consider the impact of other policies

| **Variables** | **(1)** | **(2)** | **(3)** |
|---|---|---|---|
| Panel A: *lncar* | | | |
| *treat* | -0.043*** | -0.026*** | -0.025*** |
| | (0.010) | (0.009) | (0.009) |
| *treat*1 | -0.040*** | | -0.023*** |
| | (0.006) | | (0.006) |
| *treat*2 | | -0.102*** | -0.091*** |
| | | (0.008) | (0.009) |
| *Constant* | 13.594*** | 13.699*** | 13.716*** |
| | (0.574) | (0.584) | (0.584) |
| *Control variables* | Yes | Yes | Yes |
| *City FE* | Yes | Yes | Yes |
| *Year FE* | Yes | Yes | Yes |
| *N* | 4,275 | 4,275 | 4,275 |
| {R^2} | 0.989 | 0.989 | 0.989 |
| Panel B: *lnpcar* | | | |
| *treat* | -0.054*** | -0.039*** | -0.039*** |
| | (0.010) | (0.009) | (0.009) |
| *treat*1 | -0.028*** | | -0.013** |
| | (0.005) | | (0.006) |
| *treat*2 | | -0.088*** | -0.081*** |
| | | (0.008) | (0.009) |
| *Constant* | 2.154*** | 2.254*** | 2.263*** |
| | (0.392) | (0.405) | (0.407) |
| *Control variables* | Yes | Yes | Yes |
| *City FE* | Yes | Yes | Yes |

Notes: ***, ** and * indicate statistical at 1%, 5% and 10% levels, respectively. Standard errors clustered at the city-year level are in parentheses.

| Variables | (1) | (2) | (3) |
|---|---|---|---|
| *Year FE* | Yes | Yes | Yes |
| *N* | 4,275 | 4,275 | 4,275 |
| $R^2$ | 0.981 | 0.982 | 0.982 |
| Notes: ***, ** and * indicate statistical at 1%, 5% and 10% levels, respectively. Standard errors clustered at the city-year level are in parentheses. | | | |

# 4.2.5 Other robustness analysis

This paper also conducts the following robustness tests. First, the regressions are conducted with the part of the sample with the municipality directly under the central government removed, and the results are shown in columns (1) of Table 5. Second, the time of the pilot NIDZ creation is replaced with the year when the policy document is promulgated, and the results are shown in columns (2) of Table 5. Third, this paper treats all control variables with one-period lag, and the results are shown in columns (3) of Table 5. Fourth, in order to exclude the interference of outliers, the highest and lowest 1% samples of the explanatory and control variables are treated by the tailing method, and the results are shown in columns (4) of Table 5. It can be observed that the estimated coefficients of the above four types of models for the pilot NIDZ creation are all significantly negative at the 1% statistical level, suggesting that the implementation of this pilot policy is indeed beneficial to reducing the urban carbon emissions.

Table 5
Other robustness tests

| **Variables** | **(1)** | **(2)** | **(3)** | **(4)** |
|---|---|---|---|---|
| Panel A: *lncar* | | | | |
| *treat* | -0.027*** | -0.045*** | -0.049*** | -0.058*** |
| | (0.009) | (0.010) | (0.010) | (0.011) |
| *Constant* | 12.827*** | 13.524*** | 13.962*** | 14.766*** |
| | (0.470) | (0.572) | (0.580) | (0.398) |
| *Control variables* | Yes | Yes | Yes | Yes |
| *City FE* | Yes | Yes | Yes | Yes |
| *Year FE* | Yes | Yes | Yes | Yes |
| *N* | 4,215 | 4,275 | 3,990 | 4,275 |
| {R^2} | 0.989 | 0.989 | 0.990 | 0.988 |
| Panel B: *lnpcar* | | | | |
| *treat* | -0.037*** | -0.055*** | -0.061*** | -0.034*** |
| | (0.010) | (0.010) | (0.010) | (0.010) |
| *Constant* | 1.644*** | 2.102*** | 2.080*** | 3.377*** |
| | (0.336) | (0.384) | (0.431) | (0.377) |
| *Control variables* | Yes | Yes | Yes | Yes |
| *City FE* | Yes | Yes | Yes | Yes |
| *Year FE* | Yes | Yes | Yes | Yes |
| *N* | 4,215 | 4,275 | 3,990 | 4,275 |
| {R^2} | 0.982 | 0.981 | 0.983 | 0.981 |
| Notes: ***, ** and * indicate statistical at 1%, 5% and 10% levels, respectively. Standard errors clustered at the city-year level are in parentheses. | | | | |

# 5. Mechanism Analysis

In order to test hypothesis 2, this paper further analyzes the possible mediating mechanisms of the construction of NIDZs affecting urban carbon dioxide emissions. According to the previous analysis, the carbon reduction effect of the pilot NIDZ creation may be reflected in improving the technological innovation and optimizing the industrial structure of the city. This paper measures the city’s technological innovation level by the city's comprehensive innovation index (*lni*), and the city's industrial structure by the ratio of secondary industry value added to GDP (*sind*) and the ratio of tertiary industry value added to secondary industry value added (*instr*). The above proxy variables are tested as $L_{it}$. In this paper, we adopt the method of Heckman et al. (2013), Gelbach (2016), and use following model for regression. For the sake of space, only the regression results of Eq. (7) are reported, which are shown in Table 6, with the three columns corresponding to the three variables mentioned above in turn (See Supplementary Information for full regression results).

$$Y_{it}=\alpha +\beta treat_{it}+\gamma X_{it}+u_i+\lambda _t+\varepsilon _{it} \tag{6}$$

$$L_{it}=\alpha +\beta treat_{it}+\gamma X_{it}+u_i+\lambda _t+\varepsilon _{it} \tag{7}$$

$$Y_{it}=\alpha +\beta treat_{it}+\varphi L_{it}+\gamma X_{it}+u_i+\lambda _t+\varepsilon _{it} \tag{8}$$

The regression results show that the construction of NIDZs leads to an increase in innovation index, a decrease in the share of secondary industries and an increase in the ratio of tertiary industries to secondary industries in the pilot cities. It can be observed that the implementation of the pilot policy of NIDZ creation promotes the rise of the city's technological innovation level and optimizes the city's industrial structure, which in turn suppresses urban carbon dioxide emissions. The results are consistent with the previous analysis and further confirms hypothesis 2.

Table 6
Mechanisms analysis results

| Variables | (1) | (2) | (3) |
|---|---|---|---|
| | Technology Effect | Structural Effect | |
| | *lni* | *sind* | *instr* |
| *treat* | 0.215*** | -1.741*** | 0.092*** |
| | (0.058) | (0.525) | (0.026) |
| *lnrgdp* | -0.658*** | 22.457*** | -0.723*** |
| | (0.150) | (2.189) | (0.084) |
| *lnpd* | -0.139 | 7.050 | -0.094 |
| | (0.165) | (4.299) | (0.132) |
| *sci* | 8.080*** | -6.908 | 0.194 |
| | (2.189) | (8.935) | (0.487) |
| *finc* | 0.085*** | -0.719*** | 0.038*** |
| | (0.030) | (0.223) | (0.011) |
| *lnene* | 0.038* | 1.458*** | -0.031*** |
| | (0.022) | (0.257) | (0.010) |
| *Constant* | 6.018*** | -182.123*** | 8.075*** |
| | (1.455) | (23.171) | (0.844) |
| *Control variables* | Yes | Yes | Yes |
| *City FE* | Yes | Yes | Yes |
| *Year FE* | Yes | Yes | Yes |
| *N* | 3,990 | 4,275 | 4,275 |
| {R^2} | 0.967 | 0.858 | 0.832 |
| Notes: ***, ** and * indicate statistical at 1%, 5% and 10% levels, respectively. Standard errors clustered at the city-year level are in parentheses. | | | |

## 6. Heterogeneity Analysis

The previous analysis shows that the creation of NIDZs can significantly curb urban carbon dioxide emissions, but does the carbon reduction effect of this policy still exist for cities with different characteristics? And if so, are there differences? Rather than arbitrarily introducing some common urban development characteristics, conducting a heterogeneity analysis requires determining which characteristics contribute to the creation of NIDZs. Under the innovation-driven development strategy, better-developed cities tend to have stronger factor aggregation capabilities. It promotes urban innovation and industrial structure upgrading more effectively by virtue of their advantages (Gao and Yuan, 2021). Therefore, the smooth implementation of the pilot policy cannot be achieved without mutual collaboration of human capital, fiscal expenditure, and information infrastructure, which can provide the conditions necessary for low-carbon emission reductions and environmental protection of the city to the maximum extent. It can be said that the development level of these aspects is crucial to NIDZ creation and may have a heterogeneous impact on the effect of the policy. Based on this, this paper introduces the above-mentioned indicators as the city characteristics for analysis, and analyzes the heterogeneity of NIDZ creation for carbon emission reductions in three aspects. Among them, the number of university students per 10,000 people indicates the level of human capital in the city, which measures the support in terms of human capital; the proportion of government financial expenditure to GDP indicates the capacity and quality of public services provided by government departments, which measures the support in terms of fiscal expenditure; the number of international Internet users per 10,000 people in the city indicates the level of regional information infrastructure development, which measures the support in terms of information infrastructure. In the specific empirical process, the above proxies are treated in three equal groups, and the regression analysis is conducted separately by using the first and second groups as the “low group” and the third group as the “high group”. The results are presented in Table 7.

It can be found that, in terms of human capital, the high group has better carbon reduction effect, indicating that human capital can enhance the carbon reduction effect of NIDZ creation to a certain extent. In cities with higher human capital, the work related to the construction of NIDZs is easier to carry out, and the application and innovation of low-carbon technologies are faster, which is more conducive to the creation of a green and recyclable industrial system in the city. In terms of fiscal expenditure, the regression coefficients of the dummy variable for NIDZ creation are all negative, but the coefficient is significant only in the “high group”, indicating that the carbon reduction effect of the construction of NIDZs exists only in the “high group”. The government’s fiscal expenditure ratio measures the government’s administrative intervention in the construction of NIDZs. The pilot NIDZ creation requires government policy support and investment gathering, which can only be guaranteed by a perfect policy system and sufficient funds. Moreover, fiscal expenditure can provide strong financial support for NIDZ creation, which is also an important basis for low-carbon innovation and industrial structure upgrading of enterprises. Thus the effect of reducing carbon dioxide emissions is more significant for pilot cities with higher fiscal expenditure. In terms of information infrastructure, only in the sample of “high group”, the construction of NIDZs suppressed the carbon dioxide emissions of cities. Whether the construction of information infrastructure is perfect, is also an important aspect to determine whether NIDZ creation can suppress the carbon dioxide emissions of cities. The promotion effect of information infrastructure on the carbon emission reduction effect of NIDZ creation is thus demonstrated.

Table 7
Heterogeneity analysis results

| **Variables** | **(1)** | **(2)** | **(3)** | **(4)** |
| --- | --- | --- | --- | --- |
| | *lncar* | | *lnpcar* | |
| | Low | High | Low | High |
| Panel A: Human capital levels | | | | |
| *treat* | -0.048** | -0.075*** | -0.016 | -0.121*** |
| | (0.022) | (0.015) | (0.026) | (0.020) |
| *Constant* | 15.580*** | 16.573*** | 4.393*** | 3.289*** |
| | (0.144) | (0.182) | (0.588) | (0.462) |
| *Control variables* | Yes | Yes | Yes | Yes |
| *City FE* | Yes | Yes | Yes | Yes |
| *Year FE* | Yes | Yes | Yes | Yes |
| *N* | 2,850 | 1,425 | 2,850 | 1,425 |
| {R^2} | 0.987 | 0.991 | 0.959 | 0.963 |
| Panel B: Fiscal expenditure levels | | | | |
| *treat* | -0.000 | -0.109*** | 0.003 | -0.138*** |
| | (0.016) | (0.017) | (0.016) | (0.022) |
| *Constant* | 15.987*** | 15.589*** | 3.937*** | 4.351*** |
| | (0.107) | (0.314) | (0.548) | (0.598) |
| *Control variables* | Yes | Yes | Yes | Yes |
| *City FE* | Yes | Yes | Yes | Yes |
| *Year FE* | Yes | Yes | Yes | Yes |
| *N* | 2,850 | 1,425 | 2,850 | 1,425 |
| {R^2} | 0.990 | 0.989 | 0.953 | 0.976 |
| Panel C: Information infrastructure levels | | | | |
| *treat* | 0.030 | -0.079*** | 0.018 | -0.124*** |
| | (0.026) | (0.014) | (0.037) | (0.020) |

Notes: ***, ** and * indicate statistical at 1%, 5% and 10% levels, respectively. Standard errors clustered at the city-year level are in parentheses.

| Variables | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| *Constant* | 15.647*** | 16.433*** | 4.295*** | 3.578*** |
| | (0.146) | (0.198) | (0.572) | (0.572) |
| *Control variables* | Yes | Yes | Yes | Yes |
| *City FE* | Yes | Yes | Yes | Yes |
| *Year FE* | Yes | Yes | Yes | Yes |
| *N* | 2,850 | 1,425 | 2,850 | 1,425 |
| {R^2} | 0.988 | 0.989 | 0.956 | 0.967 |
| Notes: ***, ** and * indicate statistical at 1%, 5% and 10% levels, respectively. Standard errors clustered at the city-year level are in parentheses. | | | | |

Table 8
List of pilot cities

| Pilot cities | Time |
|---|---|
| Beijing | 2009.3 |
| Wuhan | 2009.12 |
| Shanghai | 2011.3 |
| Shenzhen | 2014.6 |
| Nanjing, Suzhou, Wuxi, Changzhou, Zhenjiang | 2014.11 |
| Changsha, Zhuzhou, Xiangtan | 2015.1 |
| Tianjin | 2015.2 |
| Chengdu | 2015.6 |
| Xian, Hangzhou, Guangzhou, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, Zhaoqing | 2015.9 |
| Jinan, Qingdao, Zibo, Weifang, Yantai, Weihai, Zhengzhou, Luoyang, Xinxiang, Shenyang, Dalian | 2016.4 |
| Hefei, Wuhu, Bengbu, Fuzhou, Xiamen, Quanzhou | 2016.6 |
| Chongqing | 2016.7 |
| Lanzhou, Baiyin, Ningzhou, Wenzhou | 2018.2 |
| Wulumuqi, Changji, Shihezi | 2018.11 |
| Nanchang, Xinyu, Jingdezhen, Yingtan, Fuzhou, Jian, Ganzhou | 2019.8 |
| **Appendix B. Variable definitions** | |

Table 9
Variable symbols and definitions

| Variable Name | Symbols | Variable Definition |
|---|---|---|
| Total urban carbon dioxide emissions | *lncar* | The logarithm of automobile emissions |
| Carbon dioxide emission intensity | *lnpcar* | The logarithm of the ratio of carbon dioxide emissions to real GDP |
| The creation of NIDZs | *treat* | 1 for a city in the year of implementation of this pilot policy and each subsequent year, and 0 otherwise |
| Real GDP per capita | *lnrgdp* | The logarithm of the ratio of real GDP to total population at the end of the year |
| Energy intensity | *lnene* | The logarithm of the ratio of electricity consumption to real GDP |
| Population density | *lnpd* | The logarithm of the ratio of total population to land area in the administrative area |
| Share of secondary industry | *sind* | The proportion of the value added of secondary industry to GDP |
| Share of science and technology expenditure | *sci* | The proportion of budgetary expenditures on science and technology to budgetary fiscal expenditure |
| Financial development level | *finc* | The proportion of the loan balances of financial institutions to GDP |

# 7. Conclusions And Policy Implications

This paper considers the pilot NIDZ creation implemented in different cities at different times as a quasi-natural experiment, and analyzes the impact of NIDZ creation on urban carbon dioxide emissions using the time-varying DID method based on balanced panel data for 285 cities in China from 2003 to 2017. The conclusions of this paper suggest that the creation of NIDZs significantly reduces urban carbon dioxide emissions in pilot cities, with an average reduction of 4.8% in total carbon dioxide emissions and 5.8% in carbon emission intensity, compared to non-pilot cities. The mechanism analysis finds that the pilot policy of NIDZ creation can promote technological innovation, optimize industrial structure, and further curb urban carbon dioxide emissions. The heterogeneity analysis shows that the carbon emission reduction effect is stronger in cities with higher levels of human capital, government finance and information infrastructure.

In view of the above conclusions, the following policy implications are proposed. First, under the pressure of carbon emission reduction targets, the improvement of innovation levels is crucial to achieving green economic growth and high-quality development. This paper finds that innovation-driven development represented by the construction of NIDZs can significantly reduce urban carbon dioxide emissions, which provides an important way for China to promote low-carbon development in urban area and provides a reference to deal with the severe environmental challenges. Innovation-driven policies will not only have a positive impact on the promotion of national innovation performance, but also have significant effects on low-carbon sustainable development. The Chinese government could further expand the implementation scope of the pilot NIDZ creation and promote it throughout the country.

Secondly, local governments should be committed to exploring the industrial development models according to local conditions to effectively give full play to the carbon reduction mechanism of industrial upgrading. Improvements in technology and upgrading of industrial structures are both important aspects of achieving carbon neutrality. Moreover, local governments need to respond positively to national policies and focus on low-carbon development. The carbon emission reduction effect of NIDZ creation needs the synergy of human capital, fiscal expenditure and information infrastructure. Therefore, the government could vigorously strengthen the incentive and cultivation of innovative talents, increase the investment in enterprise R&D and enterprise transformation, and improve the level of city's information infrastructure.

Overall, from the perspective of green and low-carbon, the construction of NIDZs has achieved satisfactory results. These experiences do not only provide a strong reference for China to achieve sustainable environmental and economic development, but also provide policy tools that can be applied to carbon reduction practices in developing countries.

# Declarations

**Ethics approval and consent to participate**: Not applicable.

**Consent for Publication**: Not applicable.

**Data availability and materials**: The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

**Acknowledgment**

This research is supported by the Chinese Ministry of Education (17JJD 790015), Shaanxi Provincial Association of Social Science Society (2021ZD1043, 2021ZD1047, 2021HZ0820).

**Funding**

This research is supported by the Chinese Ministry of Education (17JJD 790015), Shaanxi Provincial Association of Social Science Society (2021ZD1043, 2021ZD1047, 2021HZ0820).

**Competing Interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Lan Fang, Heyan Tang. The first draft of the manuscript was written by Heyan Tang, Muge Mou. All authors commented on previous versions of the manuscript and approved the final manuscript.

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# Figures

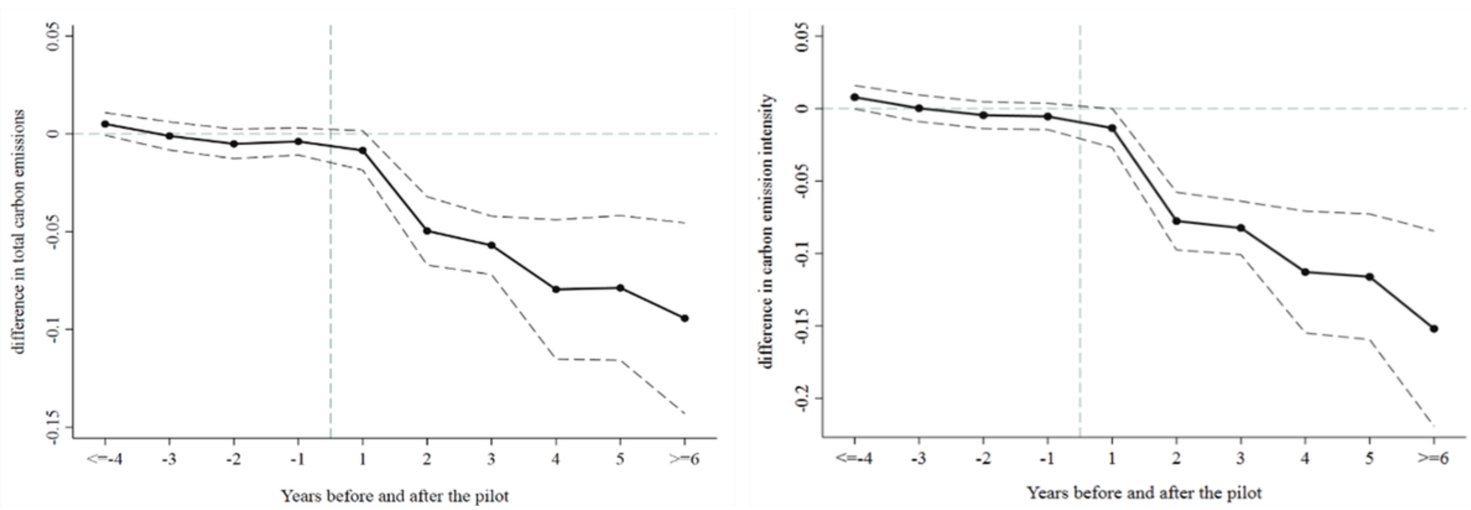


**Figure 1**

Differences in urban carbon emission levels (*lncar* (left), *lnpcar* (right))

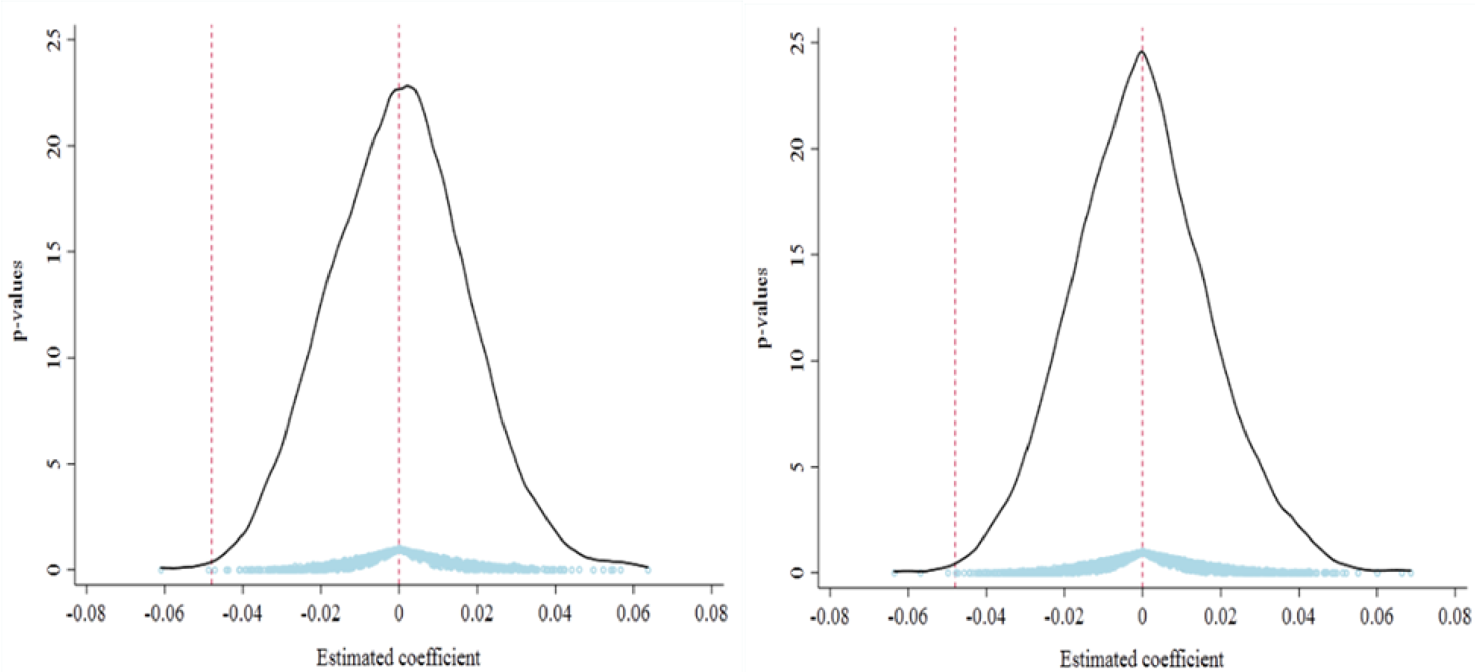


**Figure 2**

Placebo test (I) (*lncar*, 1000 (left) and 2000 (right) times)

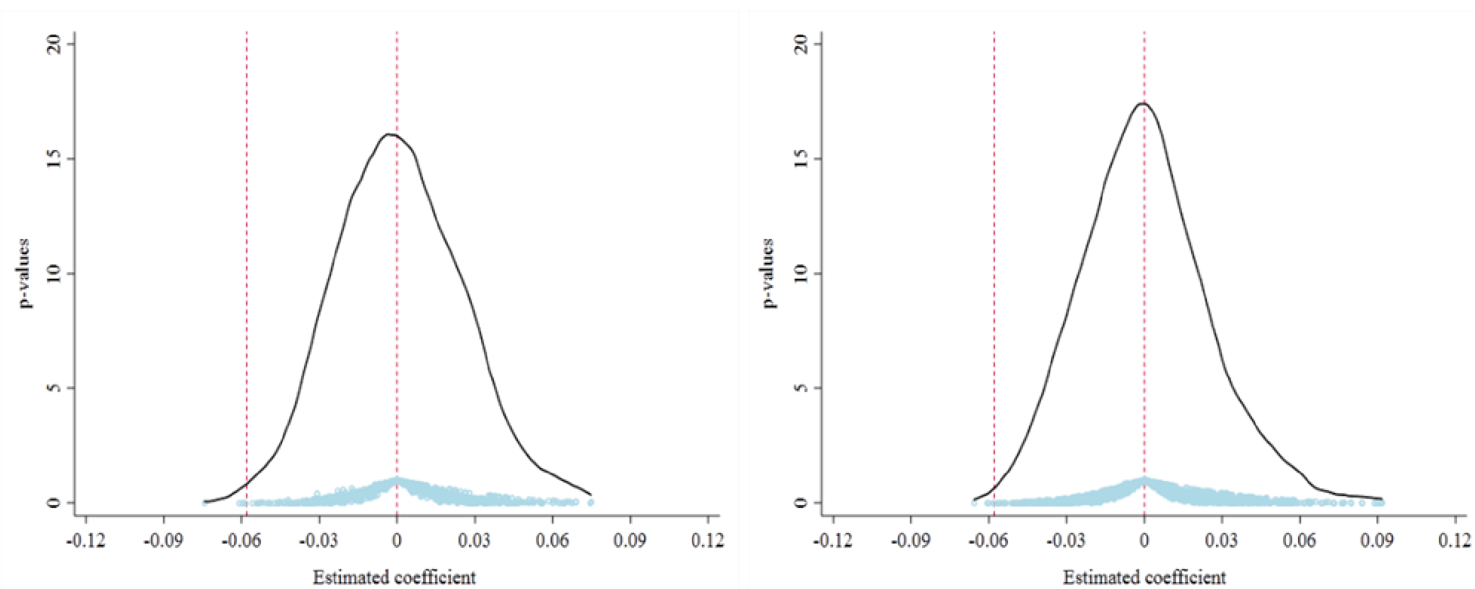


**Figure 3**

Placebo test (II) (*lnpcar*, 1000 (left) and 2000 (right) times)

# Supplementary Files

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