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REVIEW ARTICLE

Does place-based green policy improve air pollution? Evidence from China's National Eco-Industrial Demonstration Park Policy

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Abstract
Air pollution is one of the serious environmental problems facing the world. This paper systematically investigates the impact and transmission mechanism of the construction of national eco-industrial parks (NEDPs) on urban air pollution based on Chinese city-level panel data from 2003 to 2021 using a staggered difference-in-differences (staggered DID) model. It is found that the construction of NEDP significantly reduces urban air pollution, a conclusion supported by the negative weight diagnostic test and two types of robust DID estimators. Mechanism analyses indicate that NEDP construction reduces urban air pollution mainly by improving regional environmental regulation, promoting green technology innovation and improving energy structure. In addition, the mitigation effect of NEDP construction on urban air pollution is heterogeneous by policy intensity, city resource endowment, city size and administrative status. Further tests show that the institutional environment enhances the air pollution mitigation effect of NEDP construction and that the better the degree of marketization, property rights system, legal system and market development in the place where the policy is implemented, the more conducive it is to amplify the air pollution suppression effect brought about by NEDP construction. Developing economies should take complete account of the characteristics of different regions when implementing place-based green policies to achieve synergistic development of the environment and the economy.

Keywords National Eco-Industrial Demonstration Park · Air pollution · Environmental regulation · Green innovation · Energy structure · Institutional environment

Introduction

Air pollution has become one of the most severe environmental problems in the world due to industrialisation and urbanisation (Wang et al. 2019b), especially in developing countries (Feng et al. 2023). A high incidence of diseases can be caused by severe air pollution, which has not only adverse effects on human health (Zhang et al. 2022b) but also deteriorates environmental quality (Zhao et al. 2022b), inhibits agricultural development (Li et al. 2022a), discourages business production (Hanna and Oliva 2015) and impacts the sustainability of economic development. While China's crude economic growth model has led to rapid economic development, it has also made air pollution the most challenging environmental problem to solve today (Zhang et al. 2022b), with fine particles $PM_{2.5}$ being the most important source of air quality deterioration (Liu et al. 2022a). Despite launching the "*Air Pollution Prevention and Control Action Plan*" and the "*Three-Year Clean Air Action Plan*" in 2013 to "protect the blue sky", air pollution in China is still a severe phenomenon. According to the 2022 China Eco-environmental Status Bulletin released by the Chinese Ministry of Ecology and Environment in May 2023, 126 out of 339 prefecture-level cities and above in China exceeded the air quality standard in 2022, accounting for 37.2% of the total. A total of 86 cities exceeded the respirable particulate matter standard for $PM_{2.5}$, while 55 cities exceeded the standard for PM_{10}. For China to achieve sustainable economic development, it is crucial to adopt environmental policies such

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as place-based green policy. Moreover, China's experience in combating severe air pollution can also serve as a valuable reference for other developing economies (Zhao et al. 2022b).

Over the past few decades, the Chinese government has implemented various pollution prevention and control policies in response to the increasing pressure on air pollution, including national environmental regulations and place-based green policy. Place-based green policies are specific regional policies that build on place-based policies to incorporate green and sustainable development objectives. As a typical place-based policy, China has implemented development zone (DZ) policies that promote regional innovation and entrepreneurship (Tian and Xu 2022), industrial agglomeration and firm productivity (Liu et al. 2023d) and have a positive impact on regional industrial development (Zheng et al. 2016). However, with further research, some scholars have found that DZs can increase air pollution (Zhao et al. 2022a). Like DZ policies, eco-industrial parks can be considered a place-based green policy (Hua and Ye 2023). As a pillar of industrial ecology (Zhu et al. 2015), eco-industrial parks can reconcile environmental pollution with economic development (Huang et al. 2019) and are a central element of China's industrial strategy (Huang et al. 2019). In the early twenty-first century, China began to develop a strategy of eco-industrial demonstration parks (NEDPs) to establish eco-industrial parks that can serve enterprises and achieve cooperative management of resources as well as the environment, with beneficial environmental and economic effects (Valenzuela-Venegas et al. 2016). The systematic study of place-based green policy, represented by the National Eco-Industrial Demonstration Park (NEDP) Policy, can provide empirical evidence to promote regional air quality improvements. Therefore, this paper explores the impact of NEDP construction on urban air pollution using a staggered difference-in-difference (staggered DID) model using panel data at the prefecture-level city level in China from 2003 to 2021. Much of the literature suggests that place-based policy can impact regional air pollution (Hua et al. 2023); however, can place-based green policy improve local air quality? This issue has not yet received the attention of scholars.

A relevant class of literature to this paper is the research on air pollution. Air pollution is a complex mixture of compounds in the form of particles and many gases that change over time and space through atmospheric transformation (Brauer et al. 2021). Air containing low concentrations of pollutants does not pose a public health risk, but as air pollutant concentrations increase, air pollution becomes increasingly detrimental to human health (Lin et al. 2021). For measuring air pollution, scholars usually use substances such as carbon monoxide, ozone (Li et al. 2021b), sulphur dioxide (Zhang et al. 2020), nitrogen dioxide (Chen 2023), $PM_{2.5}$ and PM_{10} (Weng et al. 2022), and the Air Quality Index (Lin et al. 2021) for metrics. Air pollution has been proven to be a significant negative risk to public health and wellness, attracting increasing attention from both government and the public (Li et al. 2021a) and pushing scholars to explore the factors influencing air pollution. Regarding economic factors, Zheng et al. (2020) argue that the transformation of industrial structure will promote the economy's expansion and increase the consumption of traditional energy sources, leading to serious air pollution problems. Yun and Zhao (2022) argue that increased urbanisation exacerbates air pollution and that this effect varies with the degree of economic development. Regarding social factors, Yu et al. (2023) argue that public environmental concerns have a significant negative impact on air pollution and that increased air pollution, in turn, leads to increased public concern about environmental pollution. Yun and Zhao (2022) argue that increased urbanisation exacerbates air pollution and that this effect varies with the degree of economic development. In terms of ecological factors, meteorological conditions (Chen et al. 2019), weather patterns (Liu et al. 2022b) and changes in humidity (Liu et al. 2018) are considered to be the main ecological factors affecting air pollution. In terms of controlling air pollution, Yan et al. (2020) find that pilot emissions trading policies can reduce air pollution levels in cities by promoting the relocation of heavy-polluting industries. Li et al. (2021b) find that low-carbon pilot cities can achieve the policy goal of energy efficiency and emission reduction, which can benefit urban air pollution. Chen (2023) found that implementing smart city pilot policies can promote changes in treatment technologies and optimise the energy structure to mitigate air pollution. The NEDP policy is a plan and design for the development of eco-industrial parks that promotes the clustering of factors in the region in terms of incentives and regulation and provides an excellent operating environment for business production (Wu and Gao 2022), which contributes to the improvement of regional air pollution. How to safeguard regional air quality with place-based green policy and promote green and sustainable economic development is a major issue for developing countries, including China, and one of the motivations driving this study.

Another type of literature relevant to this paper is the research on eco-industrial parks. Eco-industrial parks are often considered parks that improve economic and environmental performance by sharing resources, cooperatively managing the environment and serving businesses (Lowe 1997). Scholars have used a variety of approaches to analyse in depth the development, role and effects of eco-industrial parks. Jung et al. (2012) used eco-industrial parks in five regions of South Korea to explore the carbon emission characteristics of their regional energy sources. Yu et al. (2014) explored the transformation process of industrial parks to eco-industrial parks and analysed the systemic development of eco-industrial parks, using the Tianjin Technological Development Zone in China as the research object. Yu et al. (2015) took Rizhao Economic and Technological Development Zone as a case study and analysed the evolutionary pattern of industrial symbiosis and eco-industrial park construction in China. Subsequently, some scholars have explored the economic impacts of NEDPs. They believe that the construction of NEDPs can promote economic growth (Hu et al. 2021), enhance regional total factor productivity and green economic efficiency (Liu et al. 2022c) and promote the progress of green technological innovation (Wu and Gao 2022). In addition, several studies have verified the environmental impact of the NEDP policy using a difference-in-difference approach. Qian et al. (2022) explored the carbon reduction effects of NEDP policies. Liu et al. (2023c) analysed the direct effects and mechanisms of action of NEDP policies on urban carbon efficiency. Zhang and Wei (2023) studied the spatial spillover effects of NEDP construction on regional eco-efficiency. However, they did not consider the problem of negative weights due to multiple treatments of time points, which may lead to biased estimation results. In addition, existing studies have mainly focused on estimating the effects of NEDP policies on carbon emission reduction and eco-efficiency while ignoring their effects on air quality improvement. In terms of policy identification strategy methods, there is currently no consensus on how to identify eco-industrial park policies, and the use of efficiency measures and case studies may produce endogeneity bias, making it difficult to accurately identify the actual impacts of NEDP policies (Qian et al. 2022). According to the Rules for the "*Declaration, Naming and Management of National Eco-Industrial Demonstration Parks (for Trial Implementation)*" issued by the Chinese Ministry of Ecology and Environment in 2003, cities building NEDPs need some park construction experience. The declaration and construction of NEDPs in the Chinese context are located in cities with experience building NDZs (place-based policy). Therefore, in contrast to the policy identification strategy of using cities without NEDPs as a control group (Wu and Gao 2022), this paper uses cities with only NDZs as a control group to better identify the true impact of NEDP policies. Such a policy identification strategy is more consistent with the reality of NEDP policy implementation, reduces the initial difference between the control and treatment groups, reduces potential selection bias and helps to clarify the true impact of NEDP policy on air pollution. Regarding conduction mechanisms, Nie et al. (2022) argue that establishing eco-industrial parks can promote technological progress. However, they do not consider the impact of NEDP on green technological innovation. Wu and Gao (2022) argue that NEDP policies can economically affect firms in a region through order-based regulatory instruments. This suggests that the construction of NEDP can benefit the environment by promoting an increase in regional environmental regulation. However, they do not empirically test the environmental regulation channel in the data context. Qian et al. (2022) find that NEDP policies can optimise the regional energy structure, while Wu et al. (2021) show that an optimised energy structure can curb air pollution. Therefore, this paper further explores the potential transmission mechanisms based on the above studies. Furthermore, the effectiveness of environmental policy implementation can be influenced by the institutional environment of a region (Han et al. 2021; Yi et al. 2019). The institutional environment varies considerably across regions in China (Huang et al. 2023), and the NEDP policy has been implemented gradually and spread across several cities in China. The literature has not yet explored the impact of the institutional environment on the effectiveness of place-based green policy implementation. This paper extends the research on NEDP policies and air pollution by including the institutional environment in the research framework, providing a helpful reference for the relationship between place-based green policy and air pollution.

This paper aims to answer the following questions. (1) Do place-based green policies, as opposed to place-based policies, affect air pollution in cities? (2) What are the transmission mechanisms by which NEDP construction affects urban air pollution? (3) Retesting the ideas of organisational resource theory, do the effects of NEDP construction policy implementation appear to be heterogeneous due to the interference of internal and external factors in cities? (4) Does the institutional environment affect the relationship between NEDP construction and urban air pollution?

The main innovations of this paper are as follows: First, this paper is one of the first papers to focus on the impact of place-based green policy on air pollution. More studies have focused on the effects of place-based policy (Hua et al. 2023), market-based policies (Yan et al. 2020) and environmental regulatory instruments (Zhang et al. 2021a) on air pollution. Little literature has focused on the environmental benefits of place-based green policy, ignoring the impact of NEDP establishment on regional air pollution. In addition, this paper presents a new argument that the simultaneous implementation of a place-based green policy can be more effective in mitigating regional air pollution than in cities that only implement place-based policies. The findings of this paper indirectly confirm that synergies can be achieved between policies with different objectives, suggesting that policies related to the promotion of economic development and policies related to environmental protection can be implemented in tandem to promote sustainable regional development. This provides new lessons for developing economies in combining and implementing policies with different orientations to achieve economic and environmental development.

Second, this paper also adopts a policy identification strategy of relatively "clean" policies and tests the application of the staggered DID model using the latest DID frontier methodology. In terms of the policy identification strategy, this paper differs from existing studies (Zhang and Wei 2023) in that the real impact of NEDP policies can be better identified by using cities with NDZ but without NEDP as a control group, taking into account the actual situation of policy implementation in China. In terms of research methodology, the latest DID theoretical econometric literature suggests that there are estimation biases in the two-way fixed effects estimates in the presence of time-heterogeneous treatment effects (de Chaisemartin and D'Haultfœuille 2020; Goodman-Bacon 2021), and most existing studies using staggered DID studies have not diagnosed and corrected for these biases, and the conclusions obtained may be biased. Therefore, this paper attempts to diagnose the bias of the effects of place-based green policy on urban air pollution using the latest research methodology to obtain the real impact of NEDP construction on air pollution.

Third, this paper delves into the mechanisms of the effects of NEDP construction on urban air pollution at a theoretical level and conducts an empirical test with Chinese data. Relevant literature has proposed channels of influence, such as industrial structure and scale effects, ignoring the role of transmission mechanisms, such as environmental regulation, green technology innovation and energy structure. This paper provides empirical support for quantitatively assessing place-based green policy's impact effects and main transmission mechanisms on regional sustainable development in developing countries.

Fourth, for the first time, the institutional environment is included in the research framework of place-based green policy and air pollution to explore the institutional factors affecting the effects of environmental policy implementation. It analyses whether the institutional environment affects the effect of NEDP established on urban air pollution from the perspectives of regional marketisation, property rights system, legal system and market development, expanding the research on NEDP established and air pollution and providing suggestions for developing economies to formulate place-based green policy that is appropriate to local characteristics.

The rest of the paper is organised as follows. "Policy background and theoretical analysis" explains the policy implementation background, theoretical analysis and research hypotheses; "Methodology and data" explains the data sources, identification strategies, variable selection and empirical models. "Main results and analysis" presents the empirical results; "Discussion" provides an in-depth discussion of the findings of this paper; "Conclusions and policy suggestions" explains the core findings of the paper and provides policy recommendations.

Policy background and theoretical analysis

Policy background

China's place-based policy system first originated in 1979 when China established its first industrial park open to the outside world: the Shekou Industrial Park. Implementing place-based policy aims to promote economic reform, improve the business environment and promote rapid regional economic growth. Such policies include the establishment of special economic zones (the Four Special Economic Zones) and industrial parks (national development zones) with particular policy preferences, the construction of location-oriented transport infrastructure (the Beijing-Shanghai high-speed railway) and energy infrastructure (the Three Gorges Dam), and the Western Development Policy (WDP), which targets relatively underdeveloped regions. The NEDP policy that is the focus of this paper belongs to the first category of place-based policy. In 2003, China's Ministry of Ecology and Environment issued the "*Rules for the Declaration, Naming and Management of National Eco-Industrial Demonstration Parks (for Trial Implementation)*", a policy document that sets out in detail the requirements for the declaration, naming and management of eco-industrial demonstration parks. Subsequently, the declaration and establishment of NEDPs began one after another. In 2007, the release of the "*Notice on the Construction of National Eco-industrial Demonstration Parks*" further promoted the process of NEDP establishment, and the establishment of NEDPs entered a rapid development stage. Guigang and Binzhou were the first to receive approval for the construction of the NEDP in 2001. In 2008, the cities of Tianjin and Suzhou received approval from the Chinese Ministry of Ecology and Environment to formally establish NEDPs, with two NEDPs established in Suzhou. In 2010, several cities (Shanghai, Rizhao, Yangzhou, etc.) received approval from the Chinese Ministry of Ecology and Environment to formally establish NEDPs. After that, the number of cities receiving approval to establish NEDPs gradually increased, spreading to many provinces and cities throughout China.

Figure 1 plots the spatial distribution of the NEDP and the selection of the control and treatment groups. The dark green dots represent NEDPs, while the light green dots represent the treatment group, i.e. cities with NEDPs. Blue represents the control group in this paper, i.e. cities with national development zones (NDZs) only. As shown in Fig. 1, 93 NEDPs have been approved in the NEDP policy list, divided into 2 main categories. One category is the approval to carry out NEDP construction work, with 45 NEDPs receiving approval to carry out NEDP construction work. In the other category, NEDPs are

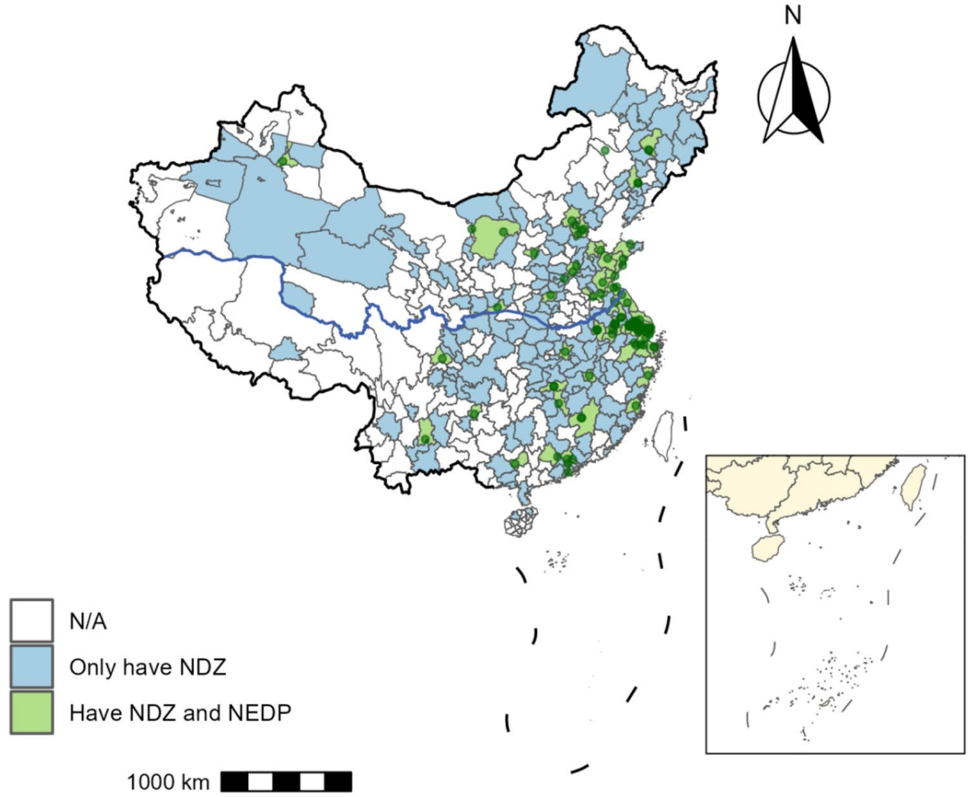


Fig. 1 Spatial distribution of the NEDP

formally established, with 48 cities receiving approval for NEDP establishment. Unlike the existing literature (Liu et al. 2022c; Qian et al. 2022; Wu et al. 2023b), this paper includes both formally established NEDP cities and cities allowed to carry out NEDP construction work. This is because considering only formally established NEDP cities may underestimate the impact of place-based green policy, and the development of NEDP construction work will inevitably have some local impact. In addition, cities with an NDZ were chosen as the control group (see blue areas in Fig. 1), as the construction of the NEDP is essentially based on cities that already have an NDZ. According to the relevant policies described in the previous section, the declaration and construction of NEDPs require that cities already have some experience building national-level zones. Therefore, this paper does not consider cities with provincial-level development zones; cities with NDZs are selected as the control group. Such a control group identification strategy is more conducive to assessing the impact of NEDP establishment on urban air pollution.

Theoretical analysis

NEDP and air pollution

Compared to place-based policy, place-based green policy has "green" characteristics, emphasising the greening of production and the sustainable development of the environment. First, establishing the NEDP strengthens the local government's assessment and regulatory standards for enterprises, raises production costs for enterprises in heavily polluting industries, encourages local enterprises in heavy industries and other polluting industries to move out, and reduces pollutant emissions and air pollution in the city. In addition, the increased regulatory standards and assessment of firms in the region will also encourage firms to seek relatively "green" production methods and to reduce their pollutant emissions in order to avoid receiving penalties from the government. Second, the construction of NEDPs raises local environmental protection requirements and promotes efficiency and technological improvements. Compared to place-based policies, the establishment of NEDPs is more oriented towards seeking synergies between the economy and the environment. In terms of production efficiency, regions establishing NEDPs will not unilaterally pursue crude production methods but rather choose efficient green production methods that are conducive to ecological development. The R&D and investment in environmental protection–related technologies can promote the transformation of the region to a resource-saving and environmentally friendly model (Liu et al. 2023a). In terms of science and technology, the establishment of the NEDP will promote the creation of a green technology platform, which is conducive to the development of energy-saving and emission reduction–related technology projects and research and development. Third, establishing NEDP will help improve local production and construction standards, promote the green transformation of highly polluting industrial enterprises and reduce local air pollutant emissions. Fourth, the establishment of the NEDP will help promote the optimisation and upgrading of the industrial structure (Liu et al. 2023c), which in turn will help improve the efficiency of resource utilisation and achieve energy saving and emission reduction (Liu et al. 2023b), and thus reduce air pollution in the region. Based on this, the following research hypotheses are proposed in this paper:

H1: Compared with cities with only DZ, establishing NEDP will reduce air pollution in cities.

Influencing mechanism

Through a literature review, this paper categorises the channels through which the establishment of the NEDP has influenced urban air pollution as "environmental regulation", "green technology innovation" and "energy structure".

First, the establishment of NEDPs may contribute to the increase in regional environmental regulation. The impact of NEDP establishment on urban air pollution can be theoretically considered a place-based policy to mitigate air pollution under increased environmental regulation (Hua and Ye 2023). The establishment of NEDPs specifies the requirements for environmental protection and faces greater environmental regulation than NDZs. The government has provided incentives for constructing NEDPs (Liu et al. 2022c), encouraging the use of green energy and reducing harmful pollutants, providing special funds for environmental protection projects, and offering subsidies and tax incentives for related projects. Therefore, establishing the NEDP may contribute to the increase in environmental regulation in the region, thereby reducing urban air pollution levels. Specifically, this could have a dampening effect on urban air pollution in the following ways:

1. According to the "reverse emissions reduction hypothesis", increased environmental regulation promotes the imposition of energy taxes on energy producers and consumers and emission charges on polluters (Chen et al. 2020a). This not only raises the cost of production for companies but also the cost to the environment, thereby reducing emissions of air pollutants.
2. Increasing regional environmental regulations will promote the relocation of highly polluting enterprises (Wu et al. 2021), pushing enterprises in highly polluting industries to move out to regions with lower environmental regulations and lower production costs, ultimately reducing regional air pollution levels.

Therefore, the following hypothesis is proposed in this paper:

H2: The construction of NEDP can reduce air pollution levels in cities by increasing the strength of regional environmental regulations.

Second, the construction of NEDP will promote the level of regional green technology innovation (Wu et al. 2023b). The place-based policy can attract high-tech companies through financial assistance and tax incentives, providing financial support for technological innovation projects and promoting technological innovation in the region (Li et al. 2023b). In contrast to place-based policies such as NDZs, NEDPs are designed to achieve regional green development, encourage clean technology research and development, and actively introduce green processes, green technologies and scientific personnel conducive to environmental protection. The accumulation of human capital and technology brought about by constructing eco-industrial parks will further enhance knowledge spillover and promote regional green technology innovation through eco-industrial clusters (Zhang et al. 2017). Therefore, the construction of NEDPs may promote the enhancement of regional green technology innovation (Wu and Gao 2022), thereby mitigating urban air pollution. Moreover, according to the "weak Porter hypothesis", environmental monitoring and management can achieve innovation compensation effects and stimulate regional innovation output. In other words, place-based green policies as environmental policies can stimulate green technological innovation. Specifically, NEDP construction will have a dampening effect on urban air pollution levels by promoting regional green technology innovation in the following ways:

1. Green technological innovation can improve the production methods of enterprises, optimise their production structures and promote the advancement of cleaner production technologies (Yi et al. 2022), which can not only reduce the problem of pollutant emissions at the source but also facilitate end-of-pipe treatment, thus reducing regional air pollution levels.
2. Green technology innovation will improve energy use efficiency (Miao et al. 2017), promote the green transformation of all types of production organisations, achieve high efficiency and greening of production systems, promote the transformation of production patterns from crude to sustainable, and achieve sustainable development of the economy and the environment, thereby reducing air pollutant emissions.

Therefore, the following research hypothesis is proposed in this paper:

H3: The construction of NEDP can reduce air pollution in cities by promoting green technological innovation.

Third, the construction of NEDP will optimise the regional energy structure. Consumption of traditional energy sources is one of the leading causes of air pollution (Wu et al. 2021). China's severe air pollution is mainly due to excessive consumption of coal resources (Li et al. 2021b). The construction of eco-industrial parks will promote introduction of Renewable Energy into the industrial system (Butturi et al. 2019), improving the energy structure to a certain extent. Specifically, the construction of eco-industrial parks facilitates the production and consumption of green electricity, energy management and energy integration (Maes et al. 2011) and saves traditional energy from the production side. In addition, as the optimisation and upgrading of the industrial structure are challenging to achieve in the short term, the establishment of NEDPs will encourage local enterprises to reduce the use of traditional fossil energy and adopt clean energy instead, promoting the optimisation of local energy structure and reducing air pollutant emissions. Therefore, the following research hypothesis is proposed in this paper:

H4: The construction of the NEDP can reduce air pollution in the city by optimising the energy structure.

NEDP, institutional environment and air pollution

In the Chinese context, where the government is the dominant player in the environmental governance process, institutional factors play a nonnegligible role in environmental protection in China (Tian et al. 2020). Some scholars have found that the effectiveness of environmental policy implementation is influenced by the local institutional environment (Li et al. 2022b) and place-based policies are also influenced by the institutional environment (Glückler 2020). As the largest developing country, China's institutional environment varies considerably across provinces (Huang et al. 2023) and is still optimised (Li and Ramanathan 2020). The institutional environment of a region is related to its property rights system, the development of intermediary organisations, the degree of sophistication of the legal system and the degree of market development (Fan et al. 2003). Protecting property rights is conducive to promoting regional innovation capacity (Lai et al. 2020). Cities with NEDPs are more likely to attract an influx of scientific and technological personnel, promoting green technological progress and improving air quality. The better the development of market intermediary organisations and the better the legal and institutional environment, the better the opportunities for market players in the region to earn higher incomes that can be used for R&D and innovation (Acemoglu and Johnson 2005). Conversely, in regions with a poor institutional environment and relatively imperfect laws and regulations, market players may circumvent policy constraints through rent-seeking behaviour, leading to relatively unfavourable policy implementation effects (Tian et al. 2020). In addition, the more mature the institutional environment, the more liquid the factor and product markets are. The more mature the factor markets, the more conducive the policy effects will be transmitted in the product and factor markets, stimulating market players to invest more in R&D, promoting green technology innovation (Lin and Chen 2018) and reducing air pollutant emissions. Given this, this paper proposes the following research hypothesis:

H5: The optimisation of the institutional environment facilitates the amplification of the suppressive effect of NEDP on urban air pollution.

Methodology and data

Policy identification strategy

The core-dependent variable in this paper is the establishment of the NEDP (*GPark*), which takes the value of 1 in year t and beyond if city i receives approval to create the NEDP in the first half of year t, and 1 in year $t+1$ and beyond if city i receives approval to create the NEDP in the second half of year t, and 0 otherwise. This measure considers the time lag in establishing the NEDP, as cities that receive approval to create the NEDP in the second half of the year are not immediately affected by the policy. Unlike existing studies (Zhang and Wei 2023), the reason for choosing cities with national development zones as the control group in this paper is that the relevant documents, such as the "*Rules for the Declaration, Naming and Management of National Eco-Industrial Demonstration Parks (for Trial Implementation)*" issued in 2003 and the "*Notice on the Construction of National Eco-Industrial Demonstration Parks*" issued in 2007 require that cities declaring the establishment of NEDPs must have particular economic strength and primary conditions for building parks, and have experience in building parks that are regionally representative and exemplary in the nation. According to the "*Catalogue of China's Development Zones Audit Bulletin*" and the "*List of National Eco-Industrial Demonstration Parks*", almost all NEDPs are declared and established in cities with national-level development zones. Therefore, cities with provincial-level development zones are not considered in this paper, but rather cities with only national-level development zones are used as the control group. This paper's control group selection strategy can reduce the initial differences between the control and treatment groups to a certain extent, reducing potential bias and obtaining a relatively "real" assessment of policy effects.

Variable selection

Dependent variables

The dependent variable in this paper is air pollution, which is measured using the logarithm of the annual average $PM_{2.5}$ concentration in cities ($LnPM_{2.5}$) and the logarithm of the annual average PM_{10} concentration in cities ($LnPM_{10}$) (Ebenstein et al. 2017; Zhang et al. 2022a). Choosing $PM_{2.5}$ and PM_{10} as air pollution measures was primarily motivated by the fact that China's rapid economic development has not only increased pollutant emissions, but also changed the source composition of air pollution (Wang et al. 2019a). The air pollution problem in China is mainly caused by haze pollution, which is dominated by $PM_{2.5}$ and PM_{10} (Zhang et al. 2019), and haze pollution is also a significant cause of global air pollution. In addition, some studies have used the AQI to measure overall air pollution levels. In 2012, China promulgated new "*Ambient Air Quality Standards*", changing the air quality monitoring data from the Air Pollution Index (API) to the Air Quality Index (AQI). AQI data have only been officially published since 2013; however, the creation of the NEDP began in 2001, and it was not until 2016 that the construction of the NEDP ended. Therefore, aerosol thickness (AOD) data from the MERRA-2 reanalysis of the National Aeronautics and Space Administration (NASA) Office of Global Modelling and Assimilation were used in this paper, taking into account the availability of data. The calculations were performed following the method of Buchard et al. (2016), and the raster data were then extracted to the city level using bilinear interpolation with ArcGIS10 software. This data has application advantages over surface-monitored mass concentrations (Ma et al. 2020) and provides monthly aerosol thickness (AOD) data for mainland China since 1980. AOD measurements can be used to predict pollution even in areas lacking ground-based monitoring stations, and this data provides a relatively comprehensive measure covering the entire country of China (Gan et al. 2022), whereas ground-based pollution data is only available for selected cities until 2013. In addition, satellite-based AOD data are statistically less different from ground-based stations after controlling for area and year fixed effects (Chen et al. 2022). Therefore, this scientifically credible data is used in many studies. Another reason for using the data provided by NASA is that the Chinese government's $PM_{2.5}$ data have only been available and published since 2012, and the data provided by NASA are also similar in trend to the data published by the Chinese Ministry of Ecology and Environment for the years available. AOD data is available at https://disc.gsfc.nasa.gov/datasets/M2TMNXAER_V5.12.4/summary?keywords=Aerosols#.

Control variables

The control variables in this paper are selected as follows: (1) Real urban GDP per capita (*LnGDPp*), as the economy grows, environmental pollution may become more serious (Ali et al. 2023), and the logarithm of real GDP per capita is used in this paper to measure urban GDP per capita. (2) Population density (*PD*), an increase in population size stimulates the consumption of resources, which in turn causes an increase in pollutant emissions (Borck and Schrauth 2021). In addition, rising population density increases economic agglomeration, increasing clean energy consumption and reducing the unit cost of energy-related public services (Chen et al. 2020b). This paper measures population density using the number of people per square kilometre. (3) Financial development (*FD*) attracts the inflow of foreign capital and promotes the development of energy-efficient technologies, thereby reducing pollutant emissions. In addition, financial development promotes economic output, which may lead to increased energy consumption and severe pollution problems (Khezri et al. 2021). This paper uses the ratio of total loans and deposits of financial institutions to regional GDP to measure this. (4) Government fiscal expenditure (*GFE*), which affects the development of a green economy (Wei et al. 2023), and hence the emission of air pollutants. This paper measures the ratio of government fiscal expenditure to GDP for cities. (5) Industrial structure (*IS*), where industrial structure optimisation is an essential driver for reducing pollutant emissions (Chen and Zhao 2019). Referring to Zhang and Chen (2023), the formula for measuring industrial structure in this paper is as follows: industrial structure = ratio of primary industry to GDP + 2 × ratio of secondary industry to GDP + 3 × ratio of tertiary industry to GDP. (6) Real estate investment (*REI*), an increase in real estate investment in cities can lead to a decrease in the amount of green space, which may harm air quality (Chen and Lee 2020). This paper measures the ratio of total real estate development investment to regional GDP in cities.

Mechanism variables

Theoretical analysis shows that establishing the NEDP will enhance environmental regulation in the region, promote the development of green technological innovation, optimise the energy structure and ultimately reduce air pollution levels in the city. The following variables are selected as mechanism variables in this paper:

(1) Environmental regulation. Measurement methods of environmental regulation can be divided into three main categories. The first type of measurement uses

environmental pollution control investment to measure environmental regulation. However, the calibre of environmental pollution control investment statistics in many Chinese cities has changed significantly since 2008. Considering the period of the data in this paper, measuring environmental regulation by the investment in environmental pollution control may lack a certain degree of precision. The second type of measurement method is to use emissions to measure environmental regulation, but this type of method is more reflective of the results of environmental regulation. The third type of measure is the use of word frequency analysis. Existing research shows that the strength of regional environmental regulation can be measured by the frequency of environmental protection keywords in government work reports (Yin et al. 2018). Drawing on Zhang et al. (2023), we used the Python software "jieba" to measure the frequency of environmental protection–related terms in prefecture-level government work reports, such as "environmental protection", "low-carbon", and "emission reduction", to measure the strength of environmental regulations in prefecture-level municipalities in terms of the proportion of related words in the total number of words (*ER1*). In addition, it was considered that using only the measure of the proportion of environmental protection–related words in the full text might overlook the semantic importance. Drawing on (Chen et al. 2018), this paper uses the proportion of the sentences in which environmental protection–related words are found in each prefecture-level municipal government work report to measure environmental regulation (*ER2*).

(2) Green technological innovation. Technological innovation is measured in more diverse ways, and the measurement methods widely adopted by scholars can be divided into the following two categories. The first type of measurement method uses R&D investment to measure technological innovation. The second type of measurement method uses green patent data. Since implementing the policy may cause arbitrage behaviour of enterprises in the region, and it is difficult to obtain data on green technology R&D investment and expenditure at the regional level, this paper mainly adopts the second type of method to measure green technology innovation. Patent data is often used to measure technological innovation (Ponta et al. 2021). This paper uses R language to crawl the International Patent Green Classification List provided by the official website of WIPO, takes the patents applied for by the State Intellectual Property Office of China as the object, identifies the patents with technical characteristics of green innovation activities and calculates the number of green invention patent applications. Subsequently, the number of green invention patent applications per 10,000 people (*GIP*) is used to measure green technology innovation in the region. Patent applications are closer to the point in time when innovation behaviour occurs than patent grants, and external environmental factors such as institutional efficiency have relatively little impact on them (Wu and Gao 2022). Therefore, this paper uses green patent applications to measure green technology innovation rather than green patent grants. In addition, this paper uses the green total factor productivity of prefecture-level cities to measure the green technological progress of cities. Due to data availability, we adopt the Super-SBM model to estimate cities' green total factor productivity (*GTFP*).

(3) Energy structure. Optimising the energy structure is conducive to developing a regional green economy and alleviating the air pollution problems caused by pollutant emissions. The theoretical part illustrates that NEDP construction will reduce the local consumption of conventional energy sources, thus optimising the energy structure. China is relatively rich in energy resources and has a huge total energy consumption, which is mainly dominated by coal consumption. Since 2010, China has begun to reduce coal consumption, and the proportion of coal consumption in total consumption has dropped from 80% in 2010 to 57.7% in 2019, resulting in large changes in the energy structure, so this paper mainly uses traditional energy consumption to measure the energy structure. Referring to Ren et al. (2021), this paper uses per capita conventional energy consumption to measure the energy consumption scale (*ECS*). Furthermore, referring to Wang et al. (2020), this paper uses total coal consumption as a share of total energy consumption to measure energy structure (*ES*), an inverse indicator, where a minor ES means a better energy structure. The ES can be expressed as follows:

$$ES_c^t = \frac{EC_c^t}{EC^t} = \frac{EC_{c1}^t + EC_{c2}^t + EC_{c3}^t + EC_{c4}^t + EC_{c5}^t + EC_{c6}^t + EC_{c7}^t}{EC^t} \tag{1}$$

Moderator variables

Referring to Li et al. (2022b), this paper adopts the total marketisation process score (*IE_MI1*) compiled by Fan et al. (2003) for each province to measure the institutional environment, with higher values representing a better institutional environment. In addition, this paper also uses the government-market relationship score (*IE_GM*), product market development score (*IE_PM*), factor market development score (*IE_FM*), intermediary organisation development and law score (*IE_Law*) from the total marketisation process refinement index to examine whether the institutional environment affects the air pollution mitigation effect of NEDP from three perspectives: property rights system, market development and contractual system respectively. This paper also calculates the marketisation index (*IE_MI2*) at the prefecture level for robustness reasons by referring to Fan et al. (2003).

Data source and processing

In this paper, the prefecture-level cities in China with an NDZ from 2003 to 2021 are used as the study sample, with 82 cities that have received approval to create an NEDP as the treatment group and other cities that only have an NDZ as the control group. Distinct from Liu et al. (2023c), this paper selects cities with NDZs but without approval to establish NEDPs as the control group, which can narrow the initial gap between the control and treatment groups and reduce potential selection bias. Data on NDZs are obtained from the "*2018 Catalogue of China's Development Zones Review Bulletin*" released by the Chinese government, and data on NEDPs are obtained from the obtained by collating the "*National Ecological Industrial Demonstration Park List*" published by the Chinese Ministry of Environment and Ecology in 2017. Air pollution data for this paper are from NASA. Other data were obtained from the China Energy Statistical Yearbook, the China Urban Statistical Yearbook, the patent application dataset provided by the China National Intellectual Property Office (CNIPA) and prefecture-level municipal government work reports. The descriptive statistics of the variables are shown in Table 1. The variables are relatively stable, with small dispersion and no significant outliers in data fluctuations.

Model selection

Basic model

The characteristics of the NEDP policy are that the central government promotes this policy in pilot projects, which can be voluntarily declared by local governments and reviewed and decided by the central government, and has the characteristics of incremental implementation, which provides the basis for this paper to adopt the staggered DID model. This paper uses the staggered DID model to examine the impact of NEDP establishment on air pollution, and the model is constructed as follows:

$$\text{LnPM2.5}_{it} = \alpha_0 + \alpha_1 \text{GPark}_{it} + \alpha_2 \sum CV + \{FE\} + \varepsilon_{it} \quad (2)$$

$$\text{LnPM10}_{it} = \beta_0 + \beta_1 \text{GPark}_{it} + \beta_2 \sum CV + \{FE\} + \varepsilon_{it} \quad (3)$$

where $LnPM_{2.5it}$ and $LnPM_{10it}$ are the logarithms of the $PM_{2.5}$ and PM_{10} concentrations in the city i in period t. The dependent variable $GPark_{it}$ is a dummy variable that takes the value of 1 in year t and beyond if the city i received approval to create an NEDP in the first half of year t and

Table 1 Descriptive statistics

Category	Variables	*N*	Mean	SD	Min	Max	Form
Dependent variables	$LnPM_{2.5}$	3781	3.810	0.360	2.551	4.661	Logarithm
	$LnPM_{10}$	3781	3.927	0.403	2.131	5.900	Logarithm
Control variables	*LnGDPp*	3781	10.464	0.890	8.046	13.185	Logarithm
	PD	3781	0.049	0.035	0.000	0.405	Proportion
	Fd	3781	2.352	1.263	0.588	6.721	Proportion
	GFE	3781	0.149	0.072	0.031	1.485	Proportion
	IS	3781	2.285	0.150	1.723	2.839	Level value
	REI	3781	0.102	0.068	0.000	0.871	Proportion
Mechanism variables	*ER1*	3781	0.004	0.002	0.000	0.020	Proportion
	ER2	3781	0.003	0.001	0.000	0.029	Proportion
	GIP	3781	0.331	0.448	0.000	3.205	Logarithm
	GTFP	3781	1.008	0.055	0.504	1.997	Level value
	ECS	3781	0.004	0.005	0.000	0.105	Proportion
	ES	3781	0.078	0.065	0.002	0.396	Proportion
Moderator variables	*IE_MI1*	3781	6.809	1.795	2.330	11.39	Score value
	IE_MI2	3781	9.908	3.128	1.959	19.69	Score value
	IE_GM	3781	6.829	1.709	1.480	10.65	Score value
	IE_PM	3781	8.372	1.160	1.310	10.61	Score value
	IE_FM	3781	5.420	2.320	0.370	17.43	Score value
	IE_Law	3781	6.235	4.165	−0.410	27.45	Score value

1 in year $t+1$ and beyond if the city i received approval to create an NEDP only in the second half of year t, and 0 otherwise. *CV* is the set of control variables, including the city's real per capita GDP (*LnGDPp*), population density (*PD*), financial development (*FD*), government fiscal expenditure (*GFE*), industrial structure (*IS*) and real estate investment (*RE*I). $FE=\{\delta i, \delta t\}$ represents city and year fixed effects, and ε_{it} represents the random disturbance term. The α_1 and β_1 in Eqs. (2) and (3) are the core coefficients of interest in this paper, and they represent the difference in air pollution between cities with NEDP and those with NDZ only. In addition, city-level clustering standard errors were used to take into account possible heteroskedasticity and autocorrelation issues.

Conduction mechanism model

This study hypothesises that NEDP policies can indirectly affect urban air pollution through environmental regulation, green technology innovation and energy structure optimisation effects. To test this hypothesis empirically, the following model is set up:

$$M_{it} = \gamma_0 + \gamma_1 \mathrm{GPark}_{it} + \gamma_2 \sum CV + \{FE\} + \varepsilon_{it} \quad (4)$$

$$\mathrm{LnPM2.5}_{it} = \delta_0 + \delta_1 \mathrm{GPark}_{it} + \delta_2 M_{it} + \delta_3 \sum CV + \{FE\} + \varepsilon_{it} \quad (5)$$

$$\mathrm{LnPM10}_{it} = \eta_0 + \eta_1 \mathrm{GPark}_{it} + \eta_2 M_{it} + \eta_3 \sum CV + \{FE\} + \varepsilon_{it} \quad (6)$$

In the above model, M_{it} represents the mechanism variables, including environmental regulation measured by word frequency analysis (*ER1*), environmental regulation measured by the share of environmentally relevant sentences (*ER2*), green invention patent applications per 10,000 people (*GIP*), green total factor productivity (*GTFP*), energy consumption scale (*ECS*) and energy structure (*ES*). The γ_1 in Eq. (4) represents the direct effect of NEDP establishment on the mechanism variable Mit, while δ_2 and η_2 in Eqs. (5) and (6) represent the effect of the mechanism variable M_{it} on urban air pollution after controlling for the NEDP establishment event.

Main results and analysis

Baseline regression analysis

This section examines the effect of the NEDP establishment on air pollution in the city. Columns (5) and (6) of Table 2 report the results of the estimation of Eqs. (2) and (3) when controlling for city FE and time FE as well as other control variables. The results show a 3.4% reduction in $PM_{2.5}$ and a 3% reduction in PM_{10} for cities with NEDP compared to cities with NDZ only. Columns (1) and (2) are the results of the

Table 2 Baseline estimation results

Variables	(1) $LnPM_{2.5}$	(2) $LnPM_{10}$	(3) $LnPM_{2.5}$	(4) $LnPM_{10}$	(5) $LnPM_{2.5}$	(6) $LnPM_{10}$	(7) $LnPM_{2.5}$	(8) $LnPM_{10}$
GPark	−0.049**	−0.044**	−0.039***	−0.038*	−0.035***	−0.030***	−0.035***	−0.030***
	(0.019)	(0.021)	(0.010)	(0.022)	(0.009)	(0.011)	(0.010)	(0.007)
LnGDPp					0.074***	0.019**	0.074***	0.019*
					(0.016)	(0.008)	(0.023)	(0.011)
PD					3.148***	2.796***	3.148***	2.796***
					(0.455)	(0.135)	(0.534)	(0.261)
Fd					0.014**	0.013***	0.014	0.013***
					(0.007)	(0.005)	(0.009)	(0.004)
GFE					−0.126	−0.752***	−0.126	−0.752***
					(0.090)	(0.083)	(0.151)	(0.087)
IS					−0.257***	−0.486***	−0.257***	−0.486***
					(0.054)	(0.044)	(0.087)	(0.047)
REI					0.322***	0.051	−0.322***	0.051
					(0.062)	(0.068)	(0.086)	(0.063)
City	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Year	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3781	3781	3781	3781	3781	3781	3781	3781
R-squared	0.092	0.002	0.887	0.741	0.894	0.773	0.894	0.773

Notes: *** $p<0.01$, ** $p<0.05$, * $p<0.1$. SEs are clustered at the city level

asymptotic double difference estimation without considering any control variables, which ignores the effects of variables such as time and city, leading to an overestimation of the air pollution mitigation effect in cities with NEDP compared to cities with NDZ only. Columns (3) and (4) are the results of the asymptotic double difference regression with the addition of time FE, and city FE, which also overestimates the results as it ignores other urban air pollution influences. Columns (7) and (8) regress the clustering to the city level, and from the results, it can be seen that cities with NEDP have mitigated air pollution compared to cities with NDZ only. This may be because cities with NEDP increase local environmental regulation, promote higher levels of green technological innovation, increase green total factor productivity in cities, optimise energy structure and thus reduce air pollution levels compared to cities with only NDZ.

Parallel trend test

Although the DID model can better circumvent the endogeneity problem, one vital premise to consider when applying the DID method to test the effect of NEDP on air pollution is that the treatment group and the control group need to maintain similar trends before establishing NEDP. Although the selection strategy for the control group in this paper is more likely to reduce the initial differences between the control and treatment groups than existing studies, it is still difficult to ensure that the control and treatment groups have similar trends prior to the onset of the policy. Considering that establishing NEDP is not a one-off nationwide exercise but a gradual exercise in each city, with a more typical expansion-type feature, this paper adopts the event study method to conduct a parallel trend test of staggered DID. The model is set up as follows:

$$\text{LnPM2.5}_{it} = \theta_0 + \sum_{j=-5}^{5} \text{GPark}(j)\theta_j + \theta_2 \sum CV + \{FE\} + \varepsilon_{it} \tag{7}$$

$$\text{LnPM10}_{it} = \lambda_0 + \sum_{j=-5}^{5} \text{GPark}(j)\lambda_j + \lambda_2 \sum CV + \{FE\} + \varepsilon_{it} \tag{8}$$

where the binary dummy variable *GPark* still indicates whether or not an NEDP is established, let K_i denote the year in which city i approved the creation of the first NEDP, define $GPark(-5) = 1$ for $t\text{-}k <= -5$ and 0 otherwise; $GPark(j) = 1$ when $t - k = j$ and 0 otherwise, $j = \{5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5$; define $GPark(5) = 1$ for $t - k> = 5$ and 0 otherwise. The rest of the model is consistent with the baseline model. If the coefficients are insignificant for $j < 0$, the estimation results satisfy the parallel trend.

The event study results are shown in Fig. 2, where the horizontal axis is the relative time to establish the NEDP, the vertical axis is the estimated coefficient, and the dashed line indicates the confidence interval at the 95% level. It can be seen that before the establishment of the NEDP, there was essentially no statistically significant difference in $PM_{2.5}$ and PM_{10} between the treatment and control groups, while after the establishment of the NEDP, $PM_{2.5}$ and PM_{10} in the treatment group decreased significantly relative to the control group, and the effect became progressively larger with time. The above analysis indicates that the staggered DID model used in this paper satisfies the parallel trend hypothesis.

The most recent DID theory literature suggests that the pre-treatment trend test cannot be used as evidence to pass the parallel trend hypothesis test. For this reason, this paper uses an honest difference-in-difference (Honest DID) model for the inference and sensitivity analysis of confidence intervals for the post-treatment point estimates, referring to a method proposed by Rambachan and Roth (2023) for testing

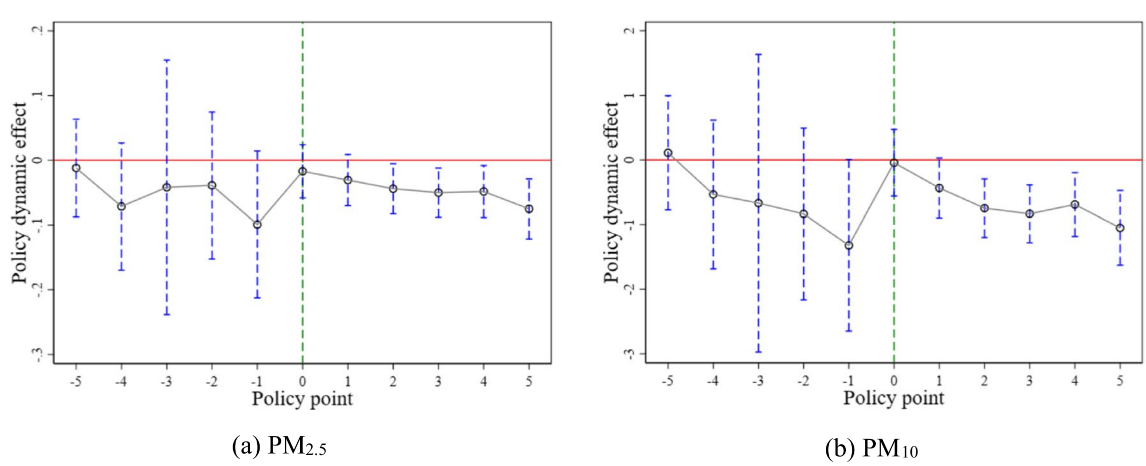


Fig. 2 Parallel trend test—event study method

when the parallel trend hypothesis is violated. This method is divided into two main steps, first constructing the maximum deviation from the parallel trend (Mbar). Then, the confidence interval for the post-treatment point estimate corresponding to Mbar is constructed. Suppose the confidence interval of the post-treatment point estimate does not contain a value of zero in the case of the maximum deviation. In that case, the treatment effect is more robust to the degree of deviation from the parallel trend. In this paper, we refer to Rambachan and Roth (2023) and set the maximum degree of deviation = 1 × standard error, which tests the treatment effect's sensitivity to parallel trends. Figure 3 shows the results of the parallel trend sensitivity test for the treatment effect in the year when the policy effect is significant under the relative degree of deviation restriction. The horizontal axis represents the maximum deviation from the parallel trend (Mbar), and the vertical axis represents the confidence interval for the post-treatment point estimate corresponding to the maximum deviation from the parallel trend (Mbar). Confidence intervals for the baseline year event study are in green in Fig. 3. As shown in Fig. 3, the NEDP establishment still significantly inhibits urban air pollution under the relative deviation degree limit.

Error diagnosis and robust DID estimators

As the two-way fixed effects DID estimates are the weighted average of multiple DID treatment effects (Goodman-Bacon 2021), the larger weights of the DID estimates for the "bad" control group can seriously affect the results of the two-way fixed effects DID estimates and the interpretation of causal effects. Given the potential bias in the estimation of staggered DID under heterogeneous treatment effects, the results of this paper are presented in Table 3 and Fig. 4 using the (Goodman-Bacon 2021) method of negative weighting. According to Goodman-Bacon (2021), cities that have not (temporarily or consistently) established NEDPs are used as a control group, which is not "contaminated" by the policy when it occurs and therefore has a relatively "clean" policy assessment effect.

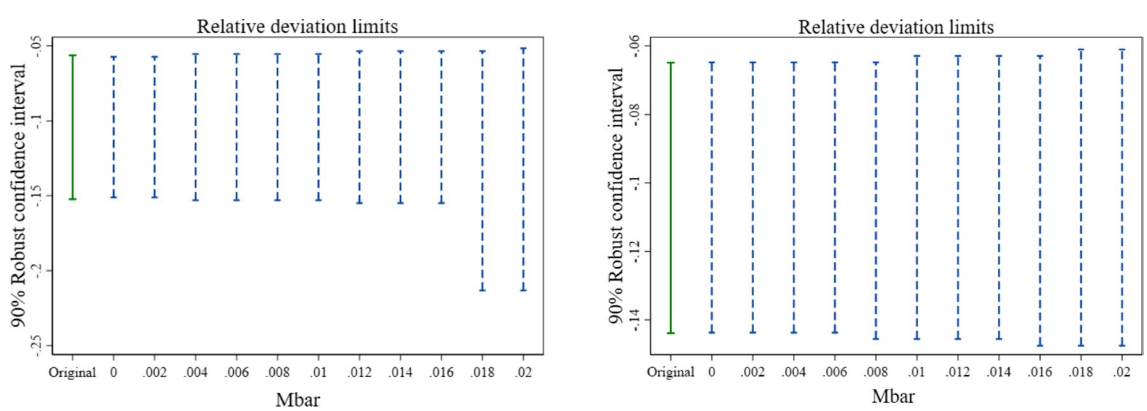
The results in Table 3 show that whether $LnPM_{2.5}$ is used as the dependent variable or $LnPM_{10}$ is used as the dependent variable, the weight of such 2 × 2DIDs for cities that have never established an NEDP as a control group exceeds 90%, which shows that the results of the baseline regression in this paper are less affected by the estimation bias caused by the inconsistent timing of the establishment of NEDPs in cities. Figure 4 shows the results of a further decomposition of the weights, where the horizontal axis is the coefficient of the DID estimator, and the vertical axis is the weight of the DID estimator. The green triangles represent the category of DID estimators with cities that have never established an NEDP as a control group. Figure 4 shows that the larger weights are basically the estimates for cities that have never established an NEDP as a control group. A few other categories have optimistic DID estimates, but the weights are small and therefore have little effect on the average treatment effect of the estimates.

The bias in two-way fixed effects models is due to heterogeneous treatment effects (de Chaisemartin and

Table 3 Negative weighted diagnostic test

Dependent variables	$LnPM_{2.5}$		$LnPM_{10}$	
GPark	− 0.067***		− 0.054**	
DID comparison	Avg DID Est	Weight	Avg DID Est	Weight
Earlier T vs. Later C	0.030	3.00%	− 0.045	5.90%
Later T vs. Earlier C	0.071	2.70%	− 0.023	1.40%
T vs. Never Treated	− 0.074	94.3%	− 0.060	92.7%

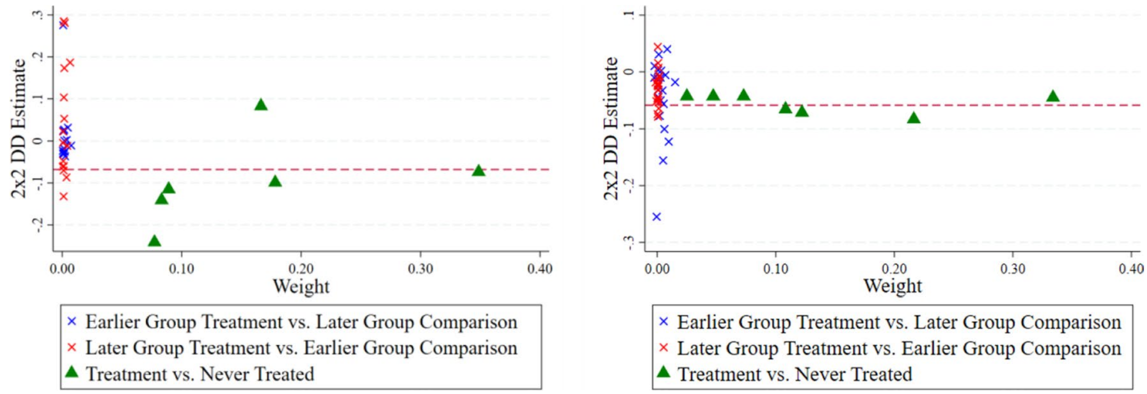
Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$



(a) $PM_{2.5}$

(b) PM_{10}

Fig. 3 Honest DID methods considering violation of parallel trends

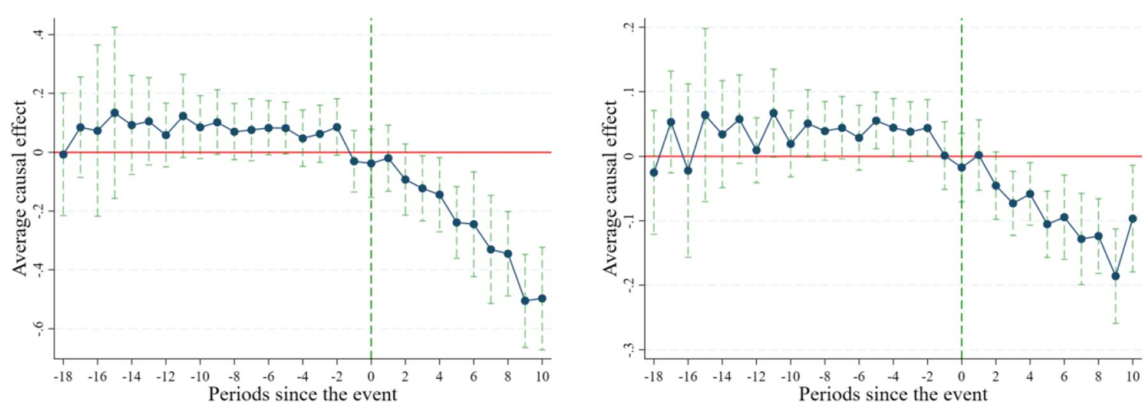


(a) $PM_{2.5}$ (b) PM_{10}

Fig. 4 Weight decomposition

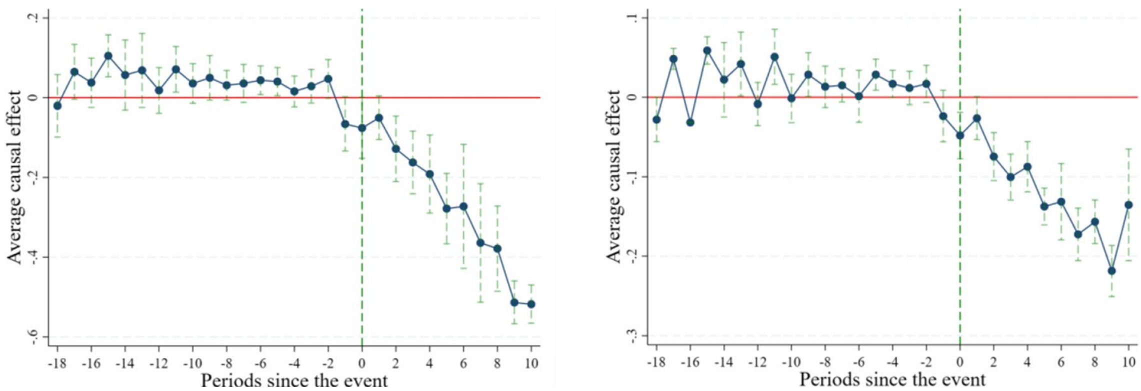
D'Haultfœuille 2020). When heterogeneous treatment effects are present, the outcome estimates of treatment effects may be biased even if the DID model satisfies the parallel trend assumption. Robust estimators can counter the problem of heterogeneous treatment effects by avoiding using treated individuals as a control group to estimate treatment effects for the treatment group. In order to address the issue of estimation bias due to heterogeneous treatment effects of staggered DID, this study uses two types of robust DID estimators for testing for heterogeneous treatment effects in the baseline model. The treatment effect is obtained by comparing the actual treatment outcome of individuals in the treatment group with their counterfactual outcome, and after weighted averaging is the unbiased estimate of the policy switching effect. The first type of robust DID estimator used in this paper is based on Sun and Abraham (2021), which uses a weighted group–time average treatment effect to estimate the policy's true impact. The second type of robust DID estimator follows Gardner (2022), which uses a two-stage DID estimator.

Figure 5 and Fig. 6 show the dynamic treatment effects before and after NEDP establishment re-estimated using the two robust estimators proposed by Sun and Abraham (2021) and Gardner (2022). The results show that the robust DID estimated coefficients were insignificant before establishing the NEDP, indicating no significant differentiation in air pollution levels in cities with NEDPs. After establishing the NEDP, the robust estimates start to be significantly negative in periods 2–3 and persist for multiple periods, further confirming the robustness of the estimation results in this paper. Overall, the NEDP establishment continues to reduce urban air pollution levels after considering the latest robust DID estimators.



(a) $PM_{2.5}$ (b) PM_{10}

Fig. 5 Robust DID statistics: the Sun and Abraham (2021) methods



(a) $PM_{2.5}$ (b) PM_{10}

Fig. 6 Robust DID statistics: the Gardner (2022) methods

Endogeneity test

Instrumental variable method

This paper further draws on the instrumental variable construction method proposed by Wu et al. (2023b) to verify the reliability of the results in order to counter the estimation bias arising from the establishment self-selection problem of the NEDP. Specifically, this paper uses the relatively exogenous urban slope as an instrumental variable for predicting NEDP establishment. In terms of relevance, establishing an NEDP requires consideration of topographic features, geological factors and traffic conditions, and a flat topography is conducive to establishing an NEDP. Regarding exclusivity, it is difficult for NEDP construction to influence urban slopes' naturally occurring geographic conditions. The three Chinese Five-Year Plans implemented during the sample period were then chosen as the exogenous period year dummy variables for predicting the establishment of NEDPs in the area, and the interaction between the inverse of urban slope and the year dummy variables was used as the instrumental variable in this paper. A two-stage least squares regression model was developed as follows:

$$\text{GPark}_{it} = \omega_0 + \omega_1 \text{GPark}_{it}^{IV} + \omega_2 \sum CV + \{FE\} + \varepsilon_{it} \quad (9)$$

$$Y_{it} = \omega_0{\prime} + \omega_1{\prime} G\widehat{P}ark_{it} + \omega_2{\prime} \sum CV + \{FE\} + \varepsilon_{it} \quad (10)$$

The regression results are presented in columns (1)–(3) of Table 4 and show that the first-stage F value of 19.744 indicates that the instrumental variable $GPark^{IV}$ is strongly

Table 4 Endogeneity test-IV, synthetic DID, PSM-DID

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	First-stage	Second-stage		Synthetic DID		PSM-DID	
VARIABLES	*GPark*	$LnPM_{2.5}$	$LnPM_{10}$	$LnPM_{2.5}$	$LnPM_{10}$	$LnPM_{2.5}$	$LnPM_{10}$
GPark		−0.349**	−0.080**	−0.039**	−0.032**	−0.046***	−0.031***
		(0.164)	(0.037)	(0.017)	(0.015)	(0.011)	(0.009)
$GPark^{IV}$	0.286***						
	(0.136)						
Constant							
F-statistic	19.744						
KP rk LM		19.054	19.056				
KP rk Wald F		82.020	82.162				
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3781	3781	3781	-	-	1574	1574
R-squared	0.517	0.855	0.977	-	-	0.657	0.701

Notes: *** $p<0.01$, ** $p<0.05$, * $p<0.1$. SEs are clustered at the city level

correlated with the dependent variable *GPark* and that the second-stage regression model results of the Kleibergen-Paap rk LM test and the Kleibergen-Paap Wald *F* test both reject the null hypothesis that the instrumental variable is underidentified and weak. The regression results show that the regression coefficients for *GPark* are both significantly negative at the 5% level, indicating that cities with NEDP have significantly lower air pollution levels compared to cities with NDZ only after accounting for endogeneity.

Synthetic difference-in-differences model

Although the DID model can circumvent the endogeneity problem to some extent, there are spatial differences in the timing and intensity of policy implementation, and the air pollution abatement effects may also vary by region, and the DID approach may not be able to accurately assess the regional differences in the timing of NEDP establishment. The DID approach may not accurately assess different regions' air pollution mitigation benefits due to the differentiated time points of NEDP establishment. Furthermore, even if the DID model passes the parallel trend test, the credibility of its conclusions is still questionable. The synthetic DID approach combines the advantages of the synthetic control and DID methods and somewhat alleviates the dependence of the estimators on the parallel trend assumption, providing more advantages in terms of robustness and estimation progress. As shown in Eq. (11), synthetic DID can retain the two-way fixed effects of DID (α_k, β_t) in a two-way fixed effects regression and includes the individual weights W_k and time weights W_t of the synthetic control method (SC), making synthetic DID more general than the DID and SC methods.

$$\left(\hat{\lambda}^{\text{SDID}}, \hat{\mu}, \hat{\alpha}, \hat{\beta}\right) = \underbrace{\arg\ \min}_{\lambda,\alpha,\beta,\mu} \left\{ \sum_{k=1}^{K} \sum_{t=1}^{T} \left(Y_{kt} - \mu - \alpha_k - \beta_t - W_{kt}\lambda\right)^2 \hat{\varpi}_k^{\text{SDID}} \hat{\varpi}_t^{\text{SDID}} \right\} \tag{11}$$

Therefore, the synthetic difference-in-differences model proposed by Arkhangelsky et al. (2021) is used in this paper to re-estimate the existence of the air pollution mitigation effect of NEDP establishment. Columns (4) and (5) of Table 4 report the estimation results based on synthetic DID, which indicate that establishing NEDP can significantly mitigate air pollution compared to cities with NDZs.

Propensity Score Matching-DID

The establishment of NEDPs may not be random. As the control group in this paper is cities with development zones, the cities declaring the establishment of NEDPs may have previously possessed the basis for establishing of NEDPs, so there may be a self-selection bias problem in this paper. This paper uses the PSM-DID method to try to solve this problem. The control variables in the baseline model are selected as matching variables, and the 1:3 nearest neighbour matching is performed on the sample, after which the matched sample is used for regression. The PSM-DID method can somewhat mitigate the interference of confounding factors in assessing the effect of the NEDP establishment policy. The matching model is as follows:

$$\begin{aligned} P\left(\text{GPark}_{it} = 1\right) = \vartheta_0 + \vartheta_1 \text{LnGDPp}_{it} + \vartheta_2 PD_{it} + \vartheta_3 FD_{it} \\ + \vartheta_4 GFE_{it} + \vartheta_5 \text{IS}_{it} + \vartheta_6 REI_{it} + \varepsilon_{it} \end{aligned} \tag{12}$$

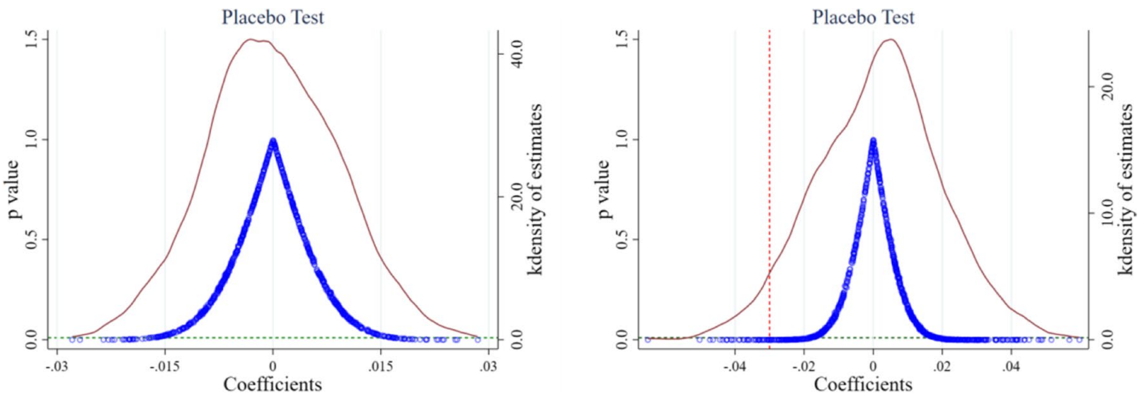
where *P* is the propensity matching score, and the results of the regression using the matched sample are presented in columns (6) and (7) of Table 4. The results show that after correcting for the sample self-selection problem, the PSM-DID regression results are similar to those obtained from the baseline regression and that the establishment of the NEDP can significantly reduce the air pollution levels in the cities in which it is located compared to cities with NDZs.

Robustness test

The baseline regression results indicate that establishing NEDP can significantly reduce the air pollution levels in the cities where it is located compared to cities with only NDZs. However, the robustness of the results needs to be further confirmed. To this end, the following approach will be adopted to conduct robustness tests.

Placebo test

In this paper, to eliminate the potential bias of NEDP construction on air pollution in the city where it is located, the time and city of NEDP establishment were randomly selected, and random sampling was repeated 800 times to conduct a placebo test. As shown in Fig. 7a and b, the density distribution of the estimates resembles a normal distribution centred on zero, demonstrating that the randomly selected cities do not exhibit a policy effect. The estimated DID regression coefficient represented by the red dashed line in Fig. 7b lies in the left tail of the placebo test regression coefficient distribution, which is a small probability event



(a) $PM_{2.5}$ (b) PM_{10}

Fig. 7 Placebo test (800 times)

in the placebo test. Therefore, the air pollution mitigation effect of NEDP establishment on the host city is objective and reliable.

Expected effects and policy exogeneity tests

The application of staggered DID requires that the experimental and control groups cannot form valid expectations about the establishment of the NEDP before it is established, requiring that the establishment of the NEDP needs to be somewhat exogenous, or it will interfere with the estimation of the results. Therefore, the following treatment is made in this paper. First, a cross-product variable, *GPark_pre*, of the time dummy variable and the NEDP establishment dummy variable for the year before NEDP establishment is constructed and included in the baseline regression model. Suppose the coefficient of this variable is significantly nonzero. In that case, it indicates that the city has formed an expectation to adjust the air pollution level before the establishment of NEDP. Second, this paper tests whether air pollution affects the timing of a city's establishment of an NEDP by referring to Xie et al. (2021), and if a city's establishment of an NEDP is influenced by air pollution, then this suggests reverse causality in the findings of this paper. Columns (1) to (4) of Table 5 report the results of the tests for expected effects and policy exogeneity. The coefficient on *GPark_pre* in columns (1) and (2) of Table 5 is not significant, indicating that the city did not develop effective anticipatory effects prior to the establishment of the NEDP. The coefficients for $LnPM_{2.5}$ and $LnPM_{10}$ in columns (3) and (4) of Table 5 are insignificant, indicating that the level of urban air pollution did not influence the timing of the establishment of the NEDP. These results suggest that cities did not form effective expectations of air pollution adjustment prior to establishing the NEDP and that the establishment of the NEDP was somewhat exogenous.

Exclude interference from other policies

Low-carbon pilot policies (Li et al. 2021b), smart city pilot policies (Chen 2023) and carbon emissions trading policies (Yan et al. 2020) have been shown to influence regional air pollution levels. Therefore, this paper refers to Liu et al. (2023b) and includes the low-carbon pilot policy dummy variable (*Policy_LC*), the smart city pilot policy dummy variable (*Policy_SC*) and the carbon emissions trading policy dummy variable (*Policy_CT*) in the baseline regression model at the same time, to test the impact of the establishment of NEDP on air pollution again. Firstly, all the above three policies are issued by the relevant departments of the Chinese central government, implemented in cities as pilot units, and have been confirmed by some studies to have an impact on regional air pollution. Second, in terms of the nodes of policy implementation, all three types of policies overlap with the establishment of the NEDP studied in this paper. For example, the first batch of pilot cities of the low-carbon pilot policy started in 2010, and the last batch of pilot cities was announced in 2017. The smart city pilot policy, on the other hand, started in 2012, and three batches of pilot cities were announced in three consecutive years. The carbon emissions trading policy began in 2013 with multiple batches. The results are shown in columns (5) and (6) of Table 5, which show that the mitigation effect of NEDP establishment on air pollution still exists under the consideration of the three policy interferences, and the robustness of the results of this paper is guaranteed.

Table 5 Robustness test—A

	(1) Expected effects	(2)	(3) Policy exogeneity test	(4)	(5) Other policy interruptions	(6)	(7) Substitution of the dependent variable	(8)
VARIABLES	$LnPM_{2.5}$	$LnPM_{10}$	*GPark*	*GPark*	$LnPM_{2.5}$	$LnPM_{10}$	SO_2	*ISE*
GPark	−0.034***	−0.032***			−0.032***	−0.027**	−0.128**	−0.078*
	(0.009)	(0.012)			(0.009)	(0.011)	(0.060)	(0.045)
GPark_pre	0.011	0.012						
	(0.010)	(0.012)						
$LnPM_{2.5}$			−0.126					
			(0.087)					
$LnPM_{10}$				0.125				
				(0.079)				
Policy_LC					−0.002	−0.019**		
					(0.008)	(0.010)		
Policy_SC					−0.005	−0.015*		
					(0.008)	(0.009)		
Policy_CT					−0.072***	−0.010		
					(0.012)	(0.017)		
City	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3781	3781	3781	3781	3781	3781	3781	3781
R-squared	0.898	0.748	0.906	0.729	0.906	0.732	0.526	0.532

Notes: *** $p<0.01$, ** $p<0.05$, * $p<0.1$. SEs are clustered at the city level

Substitution of the dependent variable

In the baseline model, we use $PM_{2.5}$ and PM_{10} as the dependent variable in the regression. To further verify the robustness of the findings, we include industrial sulphur dioxide emissions (SO_2) and industrial dust emissions (*Dust*) as dependent variables in the regression model. Columns (7) and (8) in Table 5 report the results of the robustness test after replacing the dependent variable, and the coefficients show that the establishment of NEDP also has an inhibitory effect on industrial sulphur dioxide emissions and industrial dust emissions in the region. The conclusions of this paper have a certain degree of robustness.

Replace the policy identification strategy

In the baseline model, the policy identification strategy of *GPark* takes into account the time lag of the policy. In the robustness check section, the paper replaces the policy identification strategy at the point in time when the NEDP policy is implemented, with *GPark* taking a value of 1 in the year when the NEDP is established and thereafter and 0 otherwise. The regression results for changing the policy identification strategy are shown in columns (1) and (2) of Table 6, where the coefficient of GPark remains significantly negative regardless of whether the dependent variable is $LnPM_{2.5}$ or $LnPM_{10}$. After changing the policy identification strategy at the point of NEDP establishment, the findings of this paper remain robust.

Streamlined policy list

In the previous section on policy background, it has been stated that the "*List of National Eco-Industrial Demonstration Parks*" includes both types of NEDPs. This paper considers both types of NEDPs in the baseline regression model based on the "*List of National Eco-Industrial Demonstration Parks*" issued by the Chinese Ministry of Environment and Ecology in 2017. Referring to Liu et al. (2023c), in the robustness test section, this paper only refers to the list of approved NEDPs to identify whether cities have NEDPs, and does not include the list of approved ones to carry out NEDP construction. The results are shown in columns (3) and (4) of Table 6, where the air pollution mitigation effect of NEDP establishment is still present when only the list of approved NEDPs is considered, and the results of this paper are robust.

Consider missing variables

Although the baseline model controls for the effects of many factors on air pollution at the prefecture level, the regression

Table 6 Robustness test—B

	(1)	(2)	(3)	(4)	(5)	(6)
	Replace the policy identification strategy		Streamlined policy list		Missing variable issue	
VARIABLES	$LnPM_{2.5}$	$LnPM_{10}$	$LnPM_{2.5}$	$LnPM_{10}$	$LnPM_{2.5}$	$LnPM_{10}$
GPark	−0.027***	−0.015**	−0.031***	−0.016*	−0.021***	−0.019***
	(0.006)	(0.006)	(0.012)	(0.009)	(0.009)	(0.003)
City	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Province	No	No	Yes	Yes	No	No
City&Year	No	No	No	No	Yes	Yes
Observations	3781	3781	3781	3781	3781	3781
R-squared	0.895	0.747	0.894	0.744	0.852	0.843

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. SEs are clustered at the city level

results may still be subject to estimation bias due to the presence of omitted variables, so we further incorporate city-year interaction fixed effects into the regression model to validate the robustness of the conclusions in this paper. Columns (5) and (6) of Table 6 report the regression results after controlling for the interaction fixed effects of city and year. The *GPark* coefficient remains significant, and the robustness of the findings of this paper is guaranteed.

Mechanism tests

The previous theoretical mechanism suggests that establishing NEDP will enhance local environmental regulation, promote the advancement of green technologies, optimise the energy structure and thus alleviate city air pollution levels. Increased environmental regulation will mitigate local air pollution levels (Wu et al. 2021), increased regional green technology innovation will reduce local air pollutant emissions (He et al. 2022; Yu and Zhang 2023) and optimising the energy mix will also improve regional air quality (Wu et al. 2021). Therefore, this paper will test Eqs. (4), (5), and (6) to verify the environmental regulation channel, the green technology innovation channel and the energy structure channel.

Table 7 reports the results of the tests of the environmental regulation channel. The variable *Er1* in columns (1)–(3) measures environmental regulation using the proportion of environmental protection–related words to the total number of words in each prefecture-level government work report. Considering that using only the measure of the proportion of environmental protection–related words in the whole text may ignore the semantic importance, the variable *Er2* in columns (4)–(6) is the environmental regulation measured by using the proportion of sentences in which environmental protection–related words are found in each prefecture-level municipal government work report to the total number of sentences in the whole text. The results in columns (1) and (4) show that establishing the NEDP has contributed to an increase in the level of environmental regulation in the region compared to cities with NDZs. The results in columns

Table 7 Mechanistic tests: environmental regulation effects

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	*Er1*	$LnPM_{2.5}$	$LnPM_{10}$	*Er2*	$LnPM_{2.5}$	$LnPM_{10}$
GPark	0.372**	−0.036***	−0.035***	0.320***	−0.035***	−0.035***
	(0.154)	(0.010)	(0.008)	(0.109)	(0.010)	(0.008)
Er1		−0.003**	−0.002**			
		(0.002)	(0.001)			
Er2					−0.013***	−0.008***
					(0.002)	(0.003)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3781	3781	3781	3781	3781	3781
R-squared	0.604	0.895	0.748	0.476	0.840	0.704

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. SEs are clustered at the city level

(2) and (3) and (5) and (6) both indicate that controlling for the event of the establishment of the NEDP, the increase in environmental regulation contributes to the mitigation of local air pollution levels. This implies that establishing the NEDP can improve environmental regulations in the region compared to cities with NNDZs, which reduces air pollution levels in the city. The regression results in columns (1)–(6) of Table 7 show that the environmental regulation channel is the primary channel through which the establishment of NEDPs curbs air pollution. Compared to place-based policies, NEDP policies focus more on green economic sustainability, and relevant policy documents include environmental requirements for NEDP construction. In addition, to promote the NEDP, the local government will impose strict requirements on the production and emission behaviour of the park and the local area firms, which will drive up regional environmental regulation and dampen urban air pollution.

Table 8 reports the results of testing the green technology innovation channel. The variable *GIP* in columns (1)–(3) is green technological innovation measured using the number of green invention patents per 10,000 people in each prefecture-level city. The variable *GTFP* in columns (4)–(6) is the green technological progress measured using green total factor productivity calculated by the Super-SBM model. The results in columns (1) and (4) show that the establishment of the NEDP significantly contributed to the improvement of green technological innovation and achieved green technological progress in the region compared to cities with an NDZ, in line with Wu et al. (2023b). The results in columns (2) and (3) and (5) and (6) show that green technology innovation can reduce air pollution levels in cities, controlling for the event of NEDP establishment, which is similar to the findings of Wang et al. (2023) and Yi et al. (2022). This implies that establishing NEDPs can promote green technology innovation in the region compared to cities with NDZs, thereby reducing urban air pollution. According to the regression results in columns (1)–(6) of Table 8, green technology innovation is the primary channel through which NEDPs are established to curb air pollution, thus suggesting a "weak Porter's hypothesis" effect of NEDP construction in China.

Table 9 shows the results of the energy structure optimisation channel test. This paper examines whether the establishment of the NEDP optimises the local energy structure in a way that reduces conventional energy consumption and thus curbs urban air pollution. The variable *ECS* in columns (1)–(3) is the scale of energy consumption measured using conventional energy consumption per capita. The coefficient of *ECS* in column (1) indicates that establishing NEDP reduces the per capita consumption of conventional energy in cities compared to cities with NDZ. The results in columns (2) and (3) show that reducing the scale of conventional energy consumption mitigates regional air pollution, controlling for establishing the NEDP. The *ES* in columns (4)–(6) is the energy mix measured using the share of total coal consumption in total energy consumption. The results in column (4) show that establishing the NEDP reduces the share of nonclean energy consumption, such as coal, compared to cities with an NDZ, optimising the region's energy structure. Columns (5) and (6) show that optimising the energy structure reduces air pollution levels in cities, controlling for the establishment of the NEDP. Combining the results in columns (1) and (4) shows that establishing NEDPs can reduce the consumption of conventional energy sources and thus optimise the energy structure of the region. This is similar to Qian et al. (2022), who suggest that establishing NEDPs can increase energy use efficiency and thus reduce air pollutant emissions. This implies that establishing NEDPs can optimise the energy mix and thus reduce air pollution levels in cities compared to cities with NDZs. As can be seen from the regression results in columns (1)–(6) of Table 9, it appears that the energy mix channel is the main channel through which NEDPs can reduce air pollution through the establishment of NEDPs.

Table 8 Mechanism test: weak Porter's hypothesis test (green technological innovation effect)

VARIABLES	(1) *GIP*	(2) $LnPM_{2.5}$	(3) $LnPM_{10}$	(4) *GTFP*	(5) $LnPM_{2.5}$	(6) $LnPM_{10}$
GPark	0.107***	−0.039***	−0.028**	0.012***	−0.039***	−0.028**
	(0.034)	(0.011)	(0.011)	(0.004)	(0.011)	(0.011)
GP		−0.024***	−0.021***			
		(0.005)	(0.005)			
GIP					−0.008**	−0.007*
					(0.004)	(0.004)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3781	3781	3781	3781	3781	3781
R-squared	0.917	0.841	0.959	0.437	0.845	0.959

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. SEs are clustered at the city level

Table 9 Mechanisms tested: energy structure optimisation effects

VARIABLES	(1) *ECS*	(2) $LnPM_{2.5}$	(3) $LnPM_{10}$	(4) *ES*	(5) $LnPM_{2.5}$	(6) $LnPM_{10}$
GPark	−0.001***	−0.047***	−0.028**	−0.059**	−0.037***	−0.031***
	(0.000)	(0.012)	(0.013)	(0.030)	(0.010)	(0.009)
ECS		1.893**	0.673**			
		(0.944)	(0.289)			
ES					0.016***	0.014*
					(0.006)	(0.008)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3781	3781	3781	3781	3781	3781
R-squared	0.696	0.803	0.983	0.917	0.841	0.959

Notes: *** $p<0.01$, ** $p<0.05$, * $p<0.1$. SEs are clustered at the city level

Heterogeneity analysis—a revalidation of organisational resource theory

As there are many significant disparities in administrative status, resource endowment and city size among prefecture-level cities in China, the baseline regression results based on the overall sample may obscure the air pollution mitigation effects of NEDP establishment under different city characteristics. According to organisational resource theory, the effects of policy implementation can be confounded by both internal and external factors in cities (Hitt et al. 2016). Internally, the resource endowment of the city and its size are the key factors that affect the effectiveness of NEDP policy implementation. Externally, the administrative status granted by the government can also interfere with the effectiveness of NEDP policy implementation. In addition, some cities have more than one NEDP, and there may be differences in the effects of different numbers of NEDPs on local air pollution. Therefore, this paper will analyse whether there is heterogeneity in the air pollution mitigation effects of NEDP establishment in terms of four aspects: the number of NEDPs established, resource endowment, administrative status of the city and city size.

NEDP number heterogeneity—policy intensity

We divided the sample into cities with one NEDP and cities with multiple NEDPs, based on their number of NEDPs. The results in columns (1) to (4) of Table 10 show that the *GPark* coefficients are all significantly negative, but the coefficient values are larger in cities with multiple NEDPs. This implies that having multiple NEDPs is more likely to mitigate air pollution levels in cities, similar to Zhang and Wei (2023), who argue that the effect of NEDP policies varies with the number of NEDPs. This may be because cities with a single NEDP differ significantly from those with multiple NEDPs regarding the strength of environmental regulation, environmental standards and environmental management mechanisms. Cities with multiple NEDPs are likely to emphasise production-side environmental regulation and have more

Table 10 Heterogeneity test: number of parks and administrative status of cities

	(1) Single NEDP cities	(2)	(3) Multi-NEDP cities	(4)	(5) High administrative status	(6)	(7) General administrative status	(8)
VARIABLES	$LnPM_{2.5}$	$LnPM_{10}$	$LnPM_{2.5}$	$LnPM_{10}$	$LnPM_{2.5}$	$LnPM_{10}$	$LnPM_{2.5}$	$LnPM_{10}$
GPark	−0.025***	−0.029***	−0.038***	−0.034***	−0.024	−0.016	−0.073***	−0.031***
	(0.007)	(0.008)	(0.012)	(0.007)	(0.018)	(0.012)	(0.013)	(0.010)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3292	3297	3174	3179	571	571	3210	3210
R-squared	0.894	0.744	0.897	0.744	0.901	0.972	0.895	0.718

Notes: *** $p<0.01$, ** $p<0.05$, * $p<0.1$. SEs are clustered at the city level

systematic and stringent environmental management, which dampens air pollution. In addition, the concentration of NEDPs will incentivise cities to subsidise NEDP policies. The results of the heterogeneity analysis based on the number of NEDPs also confirm that the effect of NEDP policies on air pollution varies with the intensity of the policies.

Urban administrative hierarchy heterogeneity

We divided the sample into high administrative-status cities and general administrative-status cities according to their administrative status, where high administrative-status cities mainly include China's four major municipalities, subprovincial cities and provincial capitals, and other cities are general administrative status cities. The results in columns (5) to (8) of Table 10 show that the NEDP coefficient is insignificant in high administrative status cities and is significantly negative in general administrative status cities. This implies that establishing NEDP in general administrative status in cities effectively mitigates the air pollution levels in cities. This may be because cities with high administrative status have better environmental protection facilities and relatively more mature development of green industries. Therefore, establishing NEDPs may have difficulty significantly affecting local air pollution. For cities with general administrative status, environmental regulation is relatively weak and environmental standards are relatively lower, so establishing an NEDP would be more effective in mitigating air pollution in cities with general administrative status as it would increase the level of environmental regulation in cities with general administrative status.

Resource endowments heterogeneity

Drawing on the methodology of Li et al. (2023a), the sample was divided into resource-based and non-resource-based cities based on the *National Sustainable Development Plan for Resource-Based Cities (2013–2020)* issued by the State Council of China. The results in columns (1) to (4) of Table 11 show that establishing NEDPs in resource-based cities is more likely to significantly reduce air pollution levels in the region than in non-resource-based cities. This may be because resource-based cities tend to rely on natural resources for their development. The industries in such cities tend to be dominated by the extraction and processing of resource resources (Zhang et al. 2021b), and such industries are also the primary source of air pollution in resource-based cities (Ma et al. 2018). In addition, the implementation of environmental policies also helps to raise the environmental concerns of the government and the public in resource-based cities, thus exerting pressure on high-polluting industries and enterprises and having a beneficial impact on the environment in resource-based cities (Wu et al. 2023a). Overall, establishing NEDPs has had a greater mitigating effect on air pollution in resource-based cities by enhancing local environmental regulation, promoting green technology innovation and optimising the regional energy structure.

City size heterogeneity

We divided the sample into mega-cities and small- and medium-sized cities according to the "*Notice of the State Council on Adjusting the Criteria for Classification of City Size (2014)*" issued by the State Council of China, where mega-cities refer to cities with a resident urban population of more than 5 million, while small- and medium-sized cities are those with a resident urban population of less than 5 million. The results in columns (5) to (8) of Table 11 show that the NEDP coefficients are all significantly negative but are greater in small- and medium-sized cities. Due to the structural effect, the larger the city is, the "greener" the consumption structure and the "cleaner" the energy structure (Lu et al. 2021), and the industrial structure tends to rationalise and upgrade (Yuan et al. 2018). At this point,

Table 11 Heterogeneity test: resource-based cities and city size

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Resource-based cities		Non-resource-based cities		Mega-cities		Small- and medium-sized cities	
VARIABLES	$LnPM_{2.5}$	$LnPM_{10}$	$LnPM_{2.5}$	$LnPM_{10}$	$LnPM_{2.5}$	$LnPM_{10}$	$LnPM_{2.5}$	$LnPM_{10}$
GPark	−0.035***	−0.034**	−0.024***	−0.019**	−0.022**	−0.017*	−0.046***	−0.036***
	(0.010)	(0.015)	(0.007)	(0.007)	(0.010)	(0.009)	(0.010)	(0.004)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1130	1130	2651	2651	1274	1274	2507	2507
R-squared	0.890	0.732	0.961	0.872	0.913	0.686	0.881	0.935

Notes: *** $p<0.01$, ** $p<0.05$, * $p<0.1$. SEs are clustered at the city level

establishing the NEDP has a limited impact on optimising the energy structure of large-scale cities. It thus has less effect on air pollution mitigation in mega-cities than in small and medium-sized cities.

The impact of the institutional environment on the air pollution mitigation effect of NEDP

The theoretical mechanism section suggests that the institutional environment may influence the air pollution mitigation effects of NEDP policies. To verify whether the local institutional environment influences the air pollution link effect of NEDP, the following econometric model is constructed:

$$Ln.PM2.5_{it} = \xi_0 + \xi_1 \text{GPark}_{it} + \xi_2 \text{GPark}_{it} * IE_{it} + \xi_3 IE_{it} + \xi_4 \sum CV + \{FE\} + \varepsilon_{it} \quad (13)$$

Among them, the IE_{it} is the moderator variable, which mainly includes marketisation index (*IE_MI*), government-market relationship score (*IE_GM*), product market development score (*IE_PM*), factor market development score (*IE_FM*), intermediary organisation development and law score (*IE_Law*) and other variables are consistent with the baseline model.

Table 12 presents the results of the tests of Eq. (13), and due to space constraints, in this section, we focus on reporting the effects of NEDP policies on urban $PM_{2.5}$ concentrations.

Table 12 Further examination: NEDP, institutional environment and air pollution

	(1) Degree of marketability	(2)	(3) Property rights regime	(4) Product market development	(5) Element market development	(6) Contractual regime
VARIABLES	$LnPM_{2.5}$	$LnPM_{2.5}$	$LnPM_{2.5}$	$LnPM_{2.5}$	$LnPM_{2.5}$	$LnPM_{2.5}$
GPark	−0.275***	−0.137***	−0.307***	−0.427***	−0.099***	−0.048**
	(0.052)	(0.045)	(0.066)	(0.124)	(0.037)	(0.021)
GPark×IE_MI1	−0.038***					
	(0.006)					
IE_MI1	−0.007					
	(0.006)					
GPark×IE_MI2		−0.014***				
		(0.003)				
IE_MI2		0.016***				
		(0.005)				
GPark×IE_GM			−0.050***			
			(0.009)			
IE_GM			−0.004			
			(0.004)			
GPark×IE_PM				−0.054***		
				(0.014)		
IE_PM				−0.007**		
				(0.004)		
GPark×IE_FM					−0.020***	
					(0.005)	
IE_FM					0.010***	
					(0.002)	
GPark×IE_Law						−0.008***
						(0.002)
IE_Law						−0.003*
						(0.002)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3781	3781	3781	3781	3781	3781
R-squared	0.896	0.895	0.896	0.895	0.896	0.895

Notes: *** $p<0.01$, ** $p<0.05$, * $p<0.1$. SEs are clustered at the city level

In particular, column (1) presents the results of the regression of the institutional environment (*IE_MI1*) measured by the provincial market–based index provided by Fan et al. (2003), while column (2) presents the results of the regression of the institutional environment (*IE_MI2*) measured by the market-based index at the prefecture level calculated by drawing on the measure of Fan et al. (2003). The interaction term coefficients *GPark*×*IE_MI1* and *GPark*×*IE_MI2* in columns (1) and (2) are both significantly negative, suggesting that the institutional environment positively moderates the inhibitory effect of NEDP on air pollution. Furthermore, this paper examines whether the institutional environment affects the air pollution mitigation effect of NEDP from three perspectives: property rights regime, market development and contractual regime. Columns (3)–(6) measure the local property rights regime, market development and contractual regime using the government-market relationship score (*IE_GM*), product market development score (*IE_PM*), factor market development score (*IE_FM*), intermediary organisation development and law score (*IE_Law*) from the marketisation index, respectively. The coefficients of the interaction terms in columns (3)–(6) of Table 12 are all significantly negative, indicating that the better the property rights system, the more mature the product and factor market development, and the more complete the legal system of the region the greater the effect of NEDP on local air pollution mitigation.

Discussion

While a large body of literature has examined the factors influencing air pollution, little literature has focused on the impact of place-based green policies on air pollution. This paper uses staggered DID to explore the intrinsic link between NEDP construction and urban air pollution in depth. In contrast to the existing literature, this paper also considers the problem of dealing with the interference of time-point heterogeneity in assessing policy effects. In this paper, the applicability of the staggered DID model is carefully evaluated using the bacon decomposition method and two types of DID robust estimators proposed by the recent DID theory literature. The paper then analyses in detail the mechanisms underlying the interaction between NEDP construction and urban air pollution and develops a heterogeneity test in terms of resource endowment, number of parks, city size and administrative hierarchy. As the local institutional environment often influences the effect of policy implementation, we further discuss whether the institutional environment affects the air pollution mitigation effect of NEDPs, and conduct an in-depth analysis from three aspects: property rights system, market development and contractual system. The main findings of this paper are as follows:

First, in contrast to the finding of Fan and Fang (2020) that industrial parks can cause harm to the local environment, the results of this paper using the staggered DID model show that NEDPs can significantly reduce $PM_{2.5}$ concentrations and PM_{10} concentrations in cities and mitigate local air pollution compared to cities with only NDZs. Our findings indirectly confirm the side-by-side evidence that policies with different purposes can achieve synergies, i.e. policies related to promoting economic development and policies related to environmental protection can be implemented in concert to promote sustainable regional development, which provides new lessons for developing economies in implementing policy combinations to achieve both economic and environmental development. The results of this paper are close to the findings of previous studies that the establishment of eco-industrial parks can bring about environmental improvements (Hei et al. 2022) and enhance urban eco-efficiency (Zhang and Wei 2023). According to the *"Rules for the Declaration, Naming and Management of National Eco-Industrial Demonstration Parks (for Trial Implementation)*", place-based green policies are more "green" than other place-based policies, emphasising environmental sustainability. In this regard, establishing the NEDP strengthens the local government's assessment and monitoring standards for enterprises, raises local requirements for environmental protection and promotes improving production efficiency and green technology. At the enterprise level, establishing the NEDP can also help improve local production and construction standards, promote the green transformation of highly polluting industrial enterprises and reduce air pollutant emissions.

Second, in contrast to previous studies (Wu et al. 2023b), this paper delves into the multiple mechanisms of action between NEDP construction and air pollution. Although some scholars have found the establishment of NEDPs to be beneficial in promoting green technology innovation (Liu et al. 2023c; Wu and Gao 2022), they have not focused on the rise in regional environmental regulation, improvement in energy structure and increase in green productivity resulting from the establishment of NEDPs. Environmental regulation is a critical way to address regional air pollution (Wu et al. 2021), and the increase in conventional energy consumption is one of the reasons for the increase in air pollutant emissions (Chen et al. 2013). The results of the mechanism test indicate that NEDP construction can reduce air pollution in cities by increasing environmental regulation. Similar to Wu and Gao (2022) and Wu et al. (2021), NEDP can promote the increase of regional environmental regulation, and the increase of environmental regulation can effectively mitigate the regional air pollution level. In addition, NEDP construction can also reduce urban air pollution levels by promoting green technology innovation and improving the energy structure. This suggests the existence of the "weak Porter hypothesis" in the Chinese context, whereby environmental policies are conducive to promoting technological innovation and coordinated regional development. In addition, the results of the mechanism test also confirm the "green" character of NEDP policies, which can achieve sustainable regional environmental development compared to the place-based policy.

Third, this paper validates the ideas of organisational resource theory in the Chinese context. The heterogeneous impact of NEDP construction on air pollution is examined in terms of the number of parks established, urban resource endowment, city size and administrative status, whereas previous related studies have only considered the heterogeneous impact of NEDP construction on pollution in terms of the environmental type (Liu et al. 2022c) and geographical location (Wu and Gao 2022) of cities. The results of the heterogeneity test in this paper show that the air pollution mitigation effect is more pronounced when cities have multiple NEDPs compared to a single NEDP, which, side-by-side, confirms that the increase in NEDP policy intensity is more beneficial to suppressing regional air pollution. This may be because multiple NEDP construction has a more significant effect on increasing the intensity of local environmental regulation, thereby reducing more air pollutant emissions. In addition, the results of this paper show that NEDP policy effects are mainly manifested in cities with general administrative status, which differs from the findings of Wu and Gao (2022), perhaps due to different control group selection strategies. This paper selected cities with only NDZ as the control group. Since the construction of NEDP is based on cities that already have NDZ, the policy identification strategy in this paper can reduce the differences between the control and treatment groups to a certain extent, which is conducive to estimating the real effect of NEDP policy. In addition, the heterogeneity test results indicate that the suppressive effect of NEDP construction on air pollution is more significant in resource-based and small- and medium-sized cities.

Fourth, in the further test section, we examine the moderating effect of institutional environment on NEDP establishment on air pollution; previous studies did not combine these three. The results show that improvements in the institutional environment are conducive to greater air pollution abatement by NEDP policies, which is a new finding. The institutional environment is an important factor in the success of policy implementation (Brynard 2009). In terms of the legal system, the system of incentives and penalties can provide a signalling effect for environmental policies (Li et al. 2019), which means that a good legal system can ensure that policy effects have a beneficial impact. In terms of the property rights system, the protection of property rights is conducive to improving regional air quality (Lv et al. 2023), and the improvement of the property rights system is also conducive to implementing environmental policies. Further tests show that improving the property rights system, promoting the further development of product and factor markets and establishing a mature legal system, i.e. a good institutional environment, is conducive to amplifying the beneficial effects of environmental policies, similar to Han et al. (2021).

Conclusions and policy suggestions

Conclusions

This paper explores the impact of place-based green policy on urban air pollution using a staggered DID model using panel data at the prefecture-level city level in China from 2003 to 2021. Based on the latest research literature on DID models (Sun and Abraham 2021; Gardner 2022), this paper conducts a comprehensive test of the rationality of the use of staggered DID by employing the Goodman-Bacon (2021) approach for negative weighting and by combining the latest two types of robust DID estimators to avoid the problem of estimation bias due to inconsistencies in the timing of policy implementation. In addition, considering other potential endogeneity issues, the PSM-DID model, synthetic DID model and instrumental variables approach were also used in this study. The results in this paper remain robust after placebo tests, tests for expected effects and policy exogeneity, exclusion of another policy confounding, variation in the identification strategy of treatment groups, streamlined policy list and consideration of omitted variable issues. We then examine the mechanisms underlying the effect of NEDP establishment on air pollution, examining the transmission effects of the environmental regulation channel, the green technology innovation channel and the energy structure optimisation channel. In addition, we divide the sample according to the number of NEDPs owned by cities, their resource endowment, size and administrative status to examine the heterogeneous effects of NEDP establishment on urban air pollution in a multidimensional manner. Finally, considering that NEDP policies are carried out at different times in multiple regions, and the local institutional environment may influence the policy implementation effects, this paper further examines the impact of the institutional environment on the implementation effects of NEDP policies. This study provides theoretical guidance and empirical references for developing economies to reduce air pollution by implementing place-based green policies. The main findings of this study are as follows:

(1) Place-based green policy impacts urban air pollution, and the construction of NEDP can effectively reduce air pollution levels in cities compared to cities with only NDZs.

(2) The results of the transmission mechanism show that the construction of NEDP will reduce air pollution levels in cities by strengthening regional environmental regulation, promoting green technology innovation and optimising the energy structure.
(3) The heterogeneity test results indicate that cities with multiple NEDPs have more significant air pollution mitigation effects than cities with only one NEDP. Furthermore, the air pollution mitigation effects of NEDPs are mainly found in cities with general administrative status, and the policy effects are more pronounced in resource-dependent and small and medium-sized cities.
(4) The moderating effect model suggests that optimization of the institutional environment will favourably affect the air pollution mitigation effect of the NEDP policy. The more market-oriented the city is, the better the legal and property rights system, and the more mature the product and factor markets are, the more pronounced the air pollution abatement effect of the NEDP policy.

Policy implications

Based on the main findings of this paper, some policy insights for mitigating regional air pollution are proposed.

(1) Developing economies should pay attention to the beneficial effects of locally based green policies on environmental improvement and air pollutant emissions. Eco-industrial parks should be actively promoted to achieve both ecological and industrial sustainability. In other developing economies, there is little experience in implementing place-based green policies, such as building eco-industrial demonstration parks. In the Chinese context, there are fewer cities with NEDPs, which means that the scope and space covered by such place-based green policies are limited. Therefore, for developing economies, including China, there is a need to increase awareness of the importance of place-based green policies. While attempting to build development zones (place-based policies), attention should also be paid to environmental sustainability and the beneficial impacts of eco-industrial parks.
(2) The use of differentiated green policy tools to achieve air pollution improvement based on urban variability would be beneficial for developing economies to explore targeted air pollution mitigation options. Using China as the research sample, this study finds that the inhibitory effect of NEDP on urban air pollution is affected by the city's resource endowment, administrative status, city size and other characteristic factors. This finding can also provide policy insights for developing economies. In particular, developing economies should take into consideration local conditions when implementing place-based green policies and give full play to the driving and demonstration roles of authorities and eco-industrial parks when declaring and building eco-industrial parks. In addition, the central government should introduce relevant incentive policies to promote the formation of eco-industrial parks in different regions that are compatible with local characteristics, with a view to achieving the dual effect of economic development and environmental improvement.
(3) To establish a diverse environmental regulation system for eco-industrial parks, actively promote the construction of green technology innovation platforms and attract talent incentives, and replace traditional energy with clean energy to optimise the energy structure. The results of this study show that the construction of NEDPs will reduce air pollution in cities by enhancing environmental regulation, promoting green technological innovation and optimising the energy structure.
(4) Given the moderating effect of the institutional environment on the relationship between NEDP and air pollution, local governments should improve the local institutional environment, improve the legal system and property rights system, and promote the development of markets in order to expand the beneficial effects of place-based green policies to mitigate air pollution.

Although this paper provides a detailed discussion of the effects of place-based green policies on air pollution, there are still some things that could be improved in the research process. Firstly, due to the limitations of the dataset, this study used cities as the object of study. Future research could track this topic with more microdata (e.g. firm-level data) to obtain a more accurate link between place-based green policies and air pollution. Second, although we have considered several factors that may lead to endogeneity and used a variety of methods and tools to identify the causal relationship between place-based green policies and air pollution, there may still be other factors that interfere with the identification of this causal relationship. Follow-up studies could use other methods to identify such causality.

Author contribution S. L.: conceptualisation, resources, methodology, formal analysis, writing—review and editing. L. C.: supervision, review and editing. P. X.: supervision, review and editing, corresponding author. All authors provided critical feedback and helped shape the research, analysis and manuscript.

Data availability Data are available from the authors upon request.

Declarations

Ethical approval This is an original article that does not use other information that requires ethical approval.

Consent to participate All authors participated in this article.

Consent for publication All authors have consented to this article's publication.

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