TYPE Original Research
PUBLISHED 03 June 2025
DOI 10.3389/fenvs.2025.1598729

OPEN ACCESS

EDITED BY
Ying Zhu,
Xi'an University of Architecture and Technology, China

REVIEWED BY
Chao Dai,
Sun Yat-sen University, China
Xinyu Zhang,
Capital University of Economics and Business, China
Xiangming Kong,
Beijing Polytechnic, China
Junlong Zhang,
Qingdao University, China

*CORRESPONDENCE
Xinyang Jiang,
jiangxy@bit.edu.cn

RECEIVED 23 March 2025
ACCEPTED 16 May 2025
PUBLISHED 03 June 2025

CITATION
Jiang X (2025) From burning to clean: how China's heating transition reduces pollution and enhances land-use sustainability.
Front. Environ. Sci. 13:1598729.
doi: 10.3389/fenvs.2025.1598729

From burning to clean: how China's heating transition reduces pollution and enhances land-use sustainability

Xinyang Jiang*

School of Management, Beijing Institute of Technology, Beijing, China

Introduction: Agricultural fires have posed significant challenges to environmental governance and the effective cultivation of land in China, prompting the government to implement the Clean Heating Policy (CHP) since 2013 as a key measure to reduce coal consumption and promote energy structure optimization. Moreover, growing land-use pressures—particularly those arising from agricultural intensification and rural energy demand—have further underscored the need for cleaner and more sustainable heating strategies.

Methods: Using county-level data on PM2.5 concentrations and agricultural fire frequencies, this paper employs a staggered Difference-in-Differences (DID) approach for empirical analysis.

Results: The results indicate that the CHP significantly reduces PM2.5 concentrations by 4.8% and lowers agricultural fire occurrences by 17.4%, with the findings remaining robust. Further analysis demonstrates that the air pollution mitigation effect is primarily concentrated within a 50 km radius, while the fire suppression effect extends up to 100 km, especially pronounced in core grain-producing areas and non-resource-based cities.

Discussion: Overall, this study highlights the positive role of the CHP in improving environmental quality, promoting more rational land resource use, and advancing sustainable energy transition.

KEYWORDS

clean heating policy, air pollution, agricultural fires, land-use sustainability, spillover effects, China

1 Introduction

Severe air pollution is one of the primary challenges facing China's sustainable development, posing significant threats to both environmental quality and public health. In northern China, winter heating contributes substantially to air pollution, primarily due to a heavy reliance on coal combustion, which results in elevated concentrations of pollutants such as $PM_{2.5}$, SO_2, and CO. Empirical studies have shown that the concentrations of these pollutants increase markedly during the heating season, exacerbating air quality deterioration and increasing the incidence of respiratory and cardiovascular diseases (Cao et al., 2025). In addition, biomass burning, particularly the open burning of crop residues in rural areas, remains a major source of air pollution and agricultural fires (Zhang X. et al., 2019; Hong et al., 2023). Although the government has enacted regulations banning straw burning, enforcement remains challenging in some regions. The ongoing use of crop residue burning for heating and agricultural waste disposal further aggravates air pollution levels (Mortadha et al., 2025).

In response to increasingly severe environmental pollution challenges, the Chinese government has gradually implemented the Clean Heating Policy (CHP) since 2013, which originates from Document No. 37, The Action Plan for Air Pollution Prevention and Control, issued by the State Council. The CHP aims to reduce reliance on coal, transform the energy structure, and mitigate pollution-related risks by promoting the use of cleaner heating alternatives. The core measures of the CHP include the "coal-to-gas" and "coal-to-electricity" initiatives, which encourage households and enterprises to adopt natural gas, electricity, geothermal energy, and biomass energy as substitutes for traditional coal-based heating, thereby reducing atmospheric pollutant emissions. The policy is supported by a combination of multi-level financial subsidies, infrastructure investments, and pilot programs in key regions. Specifically, the government provides subsidies for equipment purchase and installation for users participating in the "coal-to-gas" and "coal-to-electricity" programs, and offers temporary price discounts on clean energy to lower the switching costs for residents (Wu et al., 2023). In parallel, the policy promotes the expansion of natural gas pipelines, electricity grids, and centralized heating infrastructure to ensure accessibility and stability of clean heating, particularly in key areas such as Beijing-Tianjin-Hebei and the Fenwei Plain (Zhang et al., 2020).

This paper employs a staggered Difference-in-Differences (DID) model combined with high-resolution satellite remote sensing data to systematically evaluate the environmental impacts of the Clean Heating Policy (CHP). Specifically, Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data are applied to retrieve air pollutant concentrations, while fire point monitoring data are used to assess the policy's effect on agricultural fire frequency. Furthermore, a multidimensional fixed effects regression model is specified to control for weather conditions and regional heterogeneity, thereby enhancing the robustness of the estimates. In addition, heterogeneity analyses and spatial spillover assessments are conducted to explore the differential impacts of the CHP between major grain-producing areas and non-major regions, as well as the policy's influence across varying spatial scales.

The results of the analysis indicate that the Clean Heating Policy (CHP) has yielded significant environmental governance outcomes in multiple aspects. First, the CHP is found to effectively reduce air pollution levels, with PM2.5 concentrations decreasing by approximately 4.8% on average after controlling for weather variables and fixed effects. Second, the policy leads to a significant reduction in the frequency of agricultural fires, with the probability of such fires declining by around 17.4% in the year following policy implementation, and a stable downward trend continuing in subsequent years.

Moreover, the analysis identifies clear spatial spillover effects of the CHP. The improvement in air quality remains statistically significant within a 50 km radius, while the suppression effect on agricultural fires extends to distances of up to 100 km. The heterogeneity analysis further indicates that the CHP's impact on both air quality improvement and fire reduction is more pronounced in major grain-producing areas compared to non-major regions, suggesting that the policy exerts stronger effects in areas characterized by intensive agricultural activities.

This paper contributes to the existing literature in several important ways. First, while prior research has investigated the impact of clean heating policies—mostly using administrative data or ground-based air monitoring stations—few studies have simultaneously utilized high-resolution satellite remote sensing data to capture both pollution levels and agricultural fire activity (Lee M. et al., 2024; Zeng et al., 2022). By integrating MODIS-based air pollution and fire point data within a staggered Difference-in-Differences (DID) framework, a novel dual-dimensional assessment of environmental impacts is provided, improving both the precision and spatial coverage of the empirical estimation.

Second, this paper offers one of the first systematic quantifications of the spatial spillover effects of clean heating policies. Unlike previous work, which typically limits the analysis to within-city or within-province effects, the analysis constructs distance-based spillover bands (10 km, 50 km, and 100 km) and identifies a clear pattern of policy attenuation with distance (Weng et al., 2022; Chen et al., 2023). These findings contribute new empirical evidence on the spatial externalities of environmental interventions and provide a methodological reference for future research on regional environmental cooperation.

Third, the analysis extends beyond average treatment effects by addressing regional heterogeneity, distinguishing between major grain-producing areas and non-major regions (Jiang et al., 2020). The results show stronger policy effects in core agricultural zones, reflecting the interplay between rural energy use and environmental governance. These results provide practical implications for optimizing region-specific subsidy allocation and policy targeting in large-scale heating transitions.

The remainder of the paper is structured as follows. Section 2 introduces the background and implementation of the Clean Heating Policy in China's winter heating sector. Section 3 details the data sources and processing methods applied in the analysis. Section 4 presents the empirical strategy and model construction. Section 5 reports the empirical results and provides an in-depth discussion of the findings. Section 6 concludes by summarizing the main results and offering suggestions for future research directions.

2 Policy background and literature review

2.1 Background on winter heating policy in China

China's winter heating system began to take shape in the 1950s and gradually developed into a regional heating pattern divided by the "Qinling-Huaihe Line." In areas north of this line, the average temperature in January typically falls below zero degrees Celsius, making winter heating an essential need for local residents due to the long and cold winters. Over time, the heating system expanded from urban centers to rural areas; however, significant differences exist in heating methods and energy structures across regions. Urban areas primarily rely on centralized heating systems, whereas rural areas mainly adopt decentralized, individual heating solutions. These structural disparities have posed region-specific implementation challenges for clean heating transitions, while also highlighting opportunities for targeted interventions (Zhang Q. et al., 2019; Liu et al., 2020).

The winter heating system in China has traditionally been coal-based and characterized by significant technological and efficiency limitations. Research in the fields of chemistry and environmental science has demonstrated that the incomplete combustion of coal and biological straw substantially increases air pollution, resulting in the emission of large quantities of particulate matter (Liu et al., 2022; Meng, 2022). Each year, as the winter heating season begins, coal consumption rises sharply, leading to a rapid and substantial increase in air pollution levels. This issue is particularly pronounced in northern rural areas, where heating commonly relies on loose coal as the primary energy source. Such traditional heating methods are not only inefficient but also lack effective emission control, further exacerbating air quality deterioration (Qi et al., 2019). Compared with centralized urban heating systems, the decentralized individual heating systems prevalent in rural areas suffer from the absence of scale economies, making it more difficult to achieve energy conservation and emission reduction goals, and thereby exerting a more severe negative impact on regional air quality (Li et al., 2017; Chen Y. et al., 2024).

The accumulation of air pollution has caused severe negative impacts on human health, ecosystems, and economic development. From a health perspective, pollutants such as particulate matter, sulfur dioxide, and nitrogen oxides contribute to respiratory diseases, cardiovascular conditions, and even cancer, with particularly pronounced effects on vulnerable groups such as children and the elderly (Qu et al., 2020). From an ecological perspective, air pollution leads to environmental issues such as acid rain and smog, disrupting ecosystem balance, affecting crop growth, and reducing biodiversity (He S. et al., 2025). Economically, air pollution not only increases healthcare costs but also lowers labor productivity, posing a threat to the sustainable development of regional economies (Waheeb and Kocins, 2023). Against this background, the improvement of winter heating systems and the reduction of air pollution emerged as urgent environmental and social priorities in northern China.

In addition to environmental concerns, China's stated goals for carbon neutrality and its ongoing energy restructuring have played pivotal roles in shaping the Clean Heating Policy. In line with China's commitment to achieving carbon neutrality by 2060, the policy seeks to significantly reduce the nation's reliance on coal and encourage the adoption of cleaner energy alternatives, such as natural gas, electricity, and biomass. Such efforts aim not only at improving air quality but also at supporting broader environmental and decarbonization objectives. The replacement of coal-based heating systems with cleaner sources represents a key component of the country's long-term strategy for reducing carbon emissions and addressing climate change.

In recent years, a growing number of countries have explored clean heating transitions under their respective climate and energy frameworks. For instance, in Germany, the decarbonization of residential and district heating systems has been promoted through the deployment of large-scale electric heat pumps, fiscal subsidies, and the phase-out of fossil-fuel-based boilers in urban areas (Popovski et al., 2019). Meanwhile, Japan has implemented a hybrid approach that integrates CO_2 heat pump water heaters with energy-efficient building standards, particularly in cold climate regions, to reduce emissions while maintaining heating reliability (Rehman et al., 2020).

While these international approaches reflect diverse institutional contexts, they provide comparative insights into clean heating transitions applicable to the Chinese context. Germany's emphasis on renewable integration and urban infrastructure decarbonization illustrates how supply-side reforms and regional energy planning can be combined to support low-carbon transformation. In contrast, Japan's focus on end-use efficiency and technological innovation demonstrates the role of building-level improvements and behavioral change. Given China's regional disparities in infrastructure, fiscal capacity, and heating demand, a composite approach that incorporates both system-level optimization and user-level efficiency may offer a viable path for addressing urban–rural heterogeneity. These cross-national experiences underscore the relevance of adaptive, multi-level policy frameworks in advancing sustainable heating reform.

2.2 Background on clean heating policy (CHP)

China's Clean Heating Policy (CHP) was formally introduced in 2013, reflecting the central government's increasing emphasis on air pollution control. The policy was designed to reduce coal and biological straw consumption at its source and promote a transition in the energy structure. The State Council's issuance of Document No. 37, The Action Plan for Air Pollution Prevention and Control, explicitly set the target of reducing PM2.5 concentrations in the Beijing-Tianjin-Hebei region by 25% compared to 2012 levels by 2017. It also strongly advocated the substitution of coal with clean energy, with particular emphasis on promoting "coal-to-gas" and "coal-to-electricity" heating measures to improve air quality (Zheng et al., 2018). As the capital and one of the key pollution areas, Beijing served as the first pilot city for the implementation of the "coal-to-gas" initiative. Through a combination of financial subsidies and preferential natural gas pricing, the replacement of traditional coal-based heating systems with cleaner alternatives such as natural gas was widely promoted across households, enterprises, and public institutions (Wu et al., 2017).

The core components of the Clean Heating Policy (CHP) encompass the renovation of household heating equipment and the provision of multi-level cost subsidies. First, the policy explicitly mandates the upgrading of traditional coal-fired heating systems used by residents, primarily involving the replacement of decentralized coal-fired boilers with natural gas boilers, electric boilers, or other clean energy equipment. To ensure the stability and safety of clean energy utilization, the renovation process includes not only the replacement of heating devices but also the construction of supporting infrastructure such as natural gas pipeline installations and electricity grid expansions (Lu et al., 2024). However, due to the high upfront costs associated with clean heating equipment and network upgrades—particularly in economically underdeveloped regions—financial affordability remains a significant constraint on adoption.

To address this issue, the policy simultaneously introduced a cost subsidy mechanism targeting residents, covering equipment purchase subsidies, installation fee subsidies, and subsequent energy consumption subsidies. By reducing upfront renovation expenses, the subsidy framework was intended to enhance participation in the "coal-to-gas" and "coal-to-electricity" programs. Furthermore, considering that the operating costs of natural gas and electricity are generally higher than those of coal-based heating, the policy also includes seasonal energy consumption subsidies during the heating period to offset the higher costs associated with clean energy use and to mitigate the risk of limited post-conversion utilization. These subsidy measures were designed to improve affordability and support the broader adoption of clean heating systems in both urban and rural areas (Zhou et al., 2022; Shen et al., 2022).

In addition to fiscal support, the success of the Clean Heating Policy (CHP) has been facilitated by substantial investments in energy infrastructure, particularly the expansion of natural gas pipelines and electricity grids. These infrastructure investments are considered essential to enable the widespread adoption of clean heating technologies. In the absence of such infrastructure, the transition from coal-based to cleaner energy sources would be severely constrained, especially in rural and underdeveloped regions. Institutional efforts to construct and upgrade energy infrastructure have provided the necessary technical foundation for policy implementation and contributed to long-term sustainability.

Following its initial implementation in Beijing, the Clean Heating Policy (CHP) was gradually expanded to other northern regions of China, reflecting a high degree of institutional persistence and policy scalability. The policy's sustainability can be observed in three key aspects. First, financial investment has been consistently increased to support the long-term operation of subsidy programs, thereby ensuring stable and sustained economic support for households. Second, adaptive adjustments to subsidy standards and operational mechanisms have been introduced in response to local conditions, enabling the policy to better address region-specific characteristics and population needs. Third, the scope of the policy has progressively broadened, extending from urban to rural areas and facilitating the diffusion of clean heating technologies across diverse regional contexts.

Beyond environmental goals, social stability and public concerns over heating quality have also influenced the policy framework. Winter heating, particularly in northern China, constitutes not only an environmental challenge but also a critical issue of public welfare and service equity. Inadequate heating during cold winter months has been associated with widespread dissatisfaction and, in some cases, social unrest—especially in rural areas where heating systems remain outdated and inefficient. The Clean Heating Policy incorporates provisions aimed at ensuring equitable access to reliable and high-quality heating services across different regions and income groups. By addressing regional disparities in heating infrastructure, the policy contributes to improved service delivery and reduced risks of seasonal discontent, particularly during periods of extreme cold.

3 Data and variables

An unbalanced panel dataset spanning the period from 2011 to 2019 is employed, covering the core years during which the Clean Heating Policy (CHP) was formulated, initiated, and progressively implemented across various regions in northern China. The dataset comprises information on heating season schedules, policy rollout timelines, air quality indicators, fire activity records, and relevant meteorological variables.

3.1 Implementation timeline of the clean heating policy

This study systematically compiles the primary heating periods of various cities by reviewing official websites of local governments. Given the significant differences in winter temperatures across northern China, the duration of heating periods ranges from four to 8 months depending on the city. To accurately capture the actual heating conditions, I carefully document the specific start and end dates of the heating seasons for each city. Additionally, the study collects comprehensive data on the initiation dates of clean heating policies in different regions, primarily sourced from official documents and policy announcements issued by local governments. By organizing and consolidating this information, we are able to clearly define the policy implementation timelines across regions, providing a solid temporal benchmark for the subsequent empirical analysis.

3.2 Air quality data

I obtained gridded pollutant concentration data across Chinese regions from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) system, including key pollutants such as sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and fine particulate matter ($PM_{2.5}$ and PM_{10}) (Ma et al., 2019; Zhang Q. et al., 2019). The MODIS products used in this study are based on NASA's standard remote sensing pipeline, which incorporates radiometric calibration, atmospheric correction, cloud screening, and geolocation adjustment (Levy et al., 2007). These preprocessing steps ensure spatial and temporal comparability of the derived air quality indicators across regions and years.

To further ensure data quality, I followed established practice by filtering observations using MODIS quality assurance (QA) flags and removing pixels marked as low-confidence retrievals (Kloog et al., 2011; Van Donkelaar et al., 2016). The filtered data were then aggregated to the county level via spatial averaging and merged with information on local heating periods and policy implementation timelines. This process yields a consistent and reliable air quality panel dataset suitable for quasi-experimental policy evaluation.

3.3 Fire Frequency Data

The MODIS satellite provides high-resolution surface imagery with all-weather monitoring capabilities, effectively identifying and recording agricultural fire activities. I utilized professional Geographic Information System (GIS) software to conduct spatial analyses of the fire point data, extracting information on the timing and geographic locations of fire occurrences, and enhanced the reliability of the fire point data by applying stricter confidence interval thresholds (Lv et al., 2022). Furthermore, by aligning the fire point data with the implementation timelines of the Clean

Heating "coal-to-gas" policy across different regions—particularly focusing on rural areas—this study evaluates the policy's impact on the frequency of agricultural fires (Hong et al., 2023).

3.4 Meteorological data

Weather-related data, including key indicators such as temperature, humidity, and wind speed, were obtained from the National Meteorological Administration. These meteorological data provide detailed climatic background information, helping to control for external factors that may affect air quality, fire frequency, and public health outcomes (Chen W. et al., 2025; Yang and Ye, 2024). To ensure the continuity and consistency of the dataset, I conducted systematic time series analyses of the meteorological data and integrated them with the air quality data and the implementation timelines of the Clean Heating Policy. This allows for an accurate assessment of the policy's independent effects on air pollution and fire frequency (Peng et al., 2025; Liu et al., 2025).

4 Empirical strategy

To accurately evaluate the implementation effects of the winter Clean Heating Policy, a staggered Difference-in-Differences (DID) model is applied for empirical identification (Callaway and Sant'Anna, 2021; Sun and Abraham, 2021; De Chaisemartin and d'Haultfoeuille, 2020). This framework accounts for variation in the timing of policy adoption across regions and controls for potential confounding factors, thereby enhancing the internal validity of the estimation strategy.

Recent methodological literature has emphasized the importance of considering treatment effect heterogeneity under staggered adoption. While the primary estimation follows the conventional DID framework with fixed effects, the identification strategy—focusing on county-level treatment and incorporating province-year interactions—helps address biases arising from variation in policy timing and unobserved regional characteristics. In addition, an event-study analysis is implemented to assess dynamic treatment effects and evaluate the plausibility of the parallel pre-trend assumption. Specifically, the impact of the Clean Heating Policy at the county level on regional air pollution and agricultural fire frequency is estimated using a DID model specified in Equation 1:

$$\boldsymbol{Y_{it} = \alpha + \beta CHP_{it} + \gamma X_{it} + \theta_i + \mu_t + \eta_{jt} + \varepsilon_{it}} \tag{1}$$

In this model, Y_{it} represents the outcome variables, including air pollution indicators such as $PM_{2.5}$, SO_2, and NO_2 concentrations, as well as agricultural fire frequency. The key explanatory variable, $CHP_{it} = Treat_i \times Post_t$, is constructed as the interaction of two dummy variables: $Treat_i$ indicates whether county i has implemented the Clean Heating Policy, taking the value of 1 if implemented and 0 otherwise; $Post_t$ equals 1 if year t is during or after policy implementation, and 0 otherwise. X_{it} includes a set of weather-related control variables, such as temperature, humidity, wind speed, and sunshine duration, to account for other factors potentially affecting the outcome variables.

To address regional heterogeneity and enhance the credibility of the causal identification strategy, county and year fixed effects (θ_i and μ_t), along with province-year interaction fixed effects (η_{jt}), are included in the model. The county and year fixed effects jointly control for unobserved, time-invariant regional characteristics and national shocks that may affect all areas in a given year. County fixed effects absorb structural differences across counties, such as baseline infrastructure, economic composition, or heating practices, while year fixed effects account for nationwide trends, macroeconomic fluctuations, or central government policies. These fixed effects help ensure that the estimated treatment effect is not confounded by persistent regional heterogeneity or contemporaneous macro-level shocks.

Significant regional differences exist in both formal heating policies and actual heating demand across northern China. These differences are shaped by climatic conditions, infrastructure disparities, and varying local implementation strategies. To flexibly capture unobserved regional and temporal heterogeneity, province-year fixed effects are incorporated into the baseline regression model. This specification absorbs latent variation in policy execution intensity, heating practices, and province-level contemporaneous shocks. The application of province-year fixed effects is consistent with standard practices in panel data policy evaluation (Bertrand et al., 2004; Angrist and Krueger, 1999) and aligns with China's multi-level governance structure, where provincial governments play a central role in adapting and enforcing national policy directives.

To further address unobserved heterogeneity in regional policy implementation, province-year interaction fixed effects are included, which absorb time-varying shocks, variation in implementation intensity, and latent differences in local heating practices across provinces. In China's multi-level governance context, provincial governments function not only as executors of national mandates but also as key actors in adapting policies to local conditions. This specification allows for flexible control of both institutional and behavioral variation across regions and over time. By isolating variation attributable to the Clean Heating Policy from other contemporaneous province-specific influences, this approach contributes to improving the identification strategy's internal validity (Lin et al., 2021; Wang H. et al., 2024; Chen J. et al., 2024).

These fixed effects serve to account for substantial differences in how the Clean Heating Policy was implemented across provinces, including variation in rollout timing, fiscal cost-sharing arrangements, technological pathways (e.g., gas-based, electric, or hybrid systems), and enforcement coverage. Such sources of heterogeneity have been identified in recent empirical studies on regional policy implementation in China (Chen Y. et al., 2025; Xue et al., 2025).

Following Beck et al. (2010), the validity of the staggered Difference-in-Differences model hinges on a key identifying assumption: prior to policy implementation, the treatment and control groups should exhibit parallel trends in the outcome variables. That is, in the absence of the Clean Heating Policy, the outcome variables for both the treatment and control groups would follow the same growth or decline trends before and after the policy intervention. To examine the dynamic economic effects of the policy, I adopt an event study approach, with the specific model specified as Equation 2:

TABLE 1 Descriptive statistics of variables (observations = 12, 597).

Variable	Unit	Mean	Std. Dev	Min	Max
Fire frequency	—	51.131	63.167	2.849	904.403
$PM_{2.5}$	μg/m³	44.451	31.748	1.925	341.549
PM_{10}	μg/m³	48.130	78.318	0.491	396.401
Temperature	℃	12.418	9.725	−5.973	28.591
Precipitation	mm/year	1039.166	1465.090	179.942	5749.654
Humidity	%	54.057	17.024	11.112	86.556
Wind	m/s	5.145	2.125	0.646	11.549
Sunshine	h/day	5.580	2.250	3.371	15.412

$$Y_{it} = \beta_0 + \sum_{t=-3}^{6} \delta_t D_{it} + \gamma X_{it} + \theta_i + \mu_t + \eta_{jt} + \varepsilon_{it} \qquad (2)$$

In this specification, D_{it} is a set of dummy variables indicating whether county i has implemented the Clean Heating Policy in year t, taking the value of 1 if implemented and 0 otherwise. The definitions of the remaining variables are consistent with those in Equation 1. The primary focus is on the coefficient δ_t, which captures the difference between pilot and non-pilot regions in year t after the implementation of the Clean Heating Policy.

5 Main results

5.1 Descriptive statistics of samples

To illustrate the basic characteristics of the key variables, descriptive statistics are presented in Table 1. The sample consists of 1,185 county-level administrative units. The average annual frequency of agricultural fires is 51.131 occurrences, with substantial variation across counties, suggesting a highly uneven spatial distribution of fire incidents. The average concentrations of $PM_{2.5}$ and PM_{10} are 44.45 μg/m³ and 48.13 μg/m³, respectively. Large standard deviations further reflect pronounced regional disparities in air pollution levels. These summary statistics align with findings from previous studies documenting substantial differences in both air quality and agricultural burning activities across regions in China (Xu et al., 2024; Zhao et al., 2024; Lin et al., 2021).

5.2 Impact of CTG policy on air quality and fire frequency

Table 2 reports the estimation results regarding the effects of the Clean Heating Policy (CHP) on air pollution and agricultural fire frequency. The CHP is associated with statistically significant improvements in air quality. In Column (1), without controlling for covariates or fixed effects, the estimated coefficient indicates an average reduction in $PM_{2.5}$ concentrations of 5.558 μg/m³, a result that is highly significant and suggestive of a strong direct relationship between CHP implementation and pollution mitigation (Chen and Chi, 2021). When weather-related control variables are added, the estimated effect decreases to 2.15 μg/m³ but remains statistically significant. This outcome implies that meteorological fluctuations influence short-term pollution levels, but do not materially affect the estimated policy effect. Consistent findings have been reported in related studies, which confirm that "coal-to-gas" and "coal-to-electricity" programs significantly reduce concentrations of $PM_{2.5}$, SO_2, and NO_2, particularly during the heating season (Zhang et al., 2022; Wang et al., 2022).

After incorporating county-level, year, and province-year fixed effects, the regression results become more stable, with a substantial reduction in the influence of potential unobserved confounders, thereby improving the robustness of the estimated policy effects. Based on the results reported in Column (3), the Clean Heating Policy (CHP) is associated with an approximate 4.8% reduction in $PM_{2.5}$ concentrations (−2.146 μg/m³ relative to a sample mean of 44.451 μg/m³). This magnitude is calculated with reference to the sample average provided in Table 1 and indicates that, even after controlling for spatial heterogeneity, time trends, and province-level shocks, the estimated effects remain statistically meaningful. These

TABLE 2 Effect of coal-to-gas policy (CTG) on air pollution and fire frequency.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	$PM_{2.5}$ (μg/m³)			Fire frequency		
CHP	−5.558*** (0.205)	−2.152*** (0.217)	−2.146*** (0.433)	−7.621*** (1.791)	−8.146*** (1.315)	−8.921*** (1.574)
Weather controls	No	Yes	Yes	No	Yes	Yes
Year FE	No	No	Yes	No	No	Yes
County FE	No	No	Yes	No	No	Yes
Province-year FE	No	No	Yes	No	No	Yes
R-squared	0.452	0.524	0.601	0.594	0.569	0.594
Observations	12, 597	12, 597	12, 597	12, 597	12, 597	12, 597

Note: Columns (1–3) show the effect of CHP, on air pollution, and columns (4–6) show the effect of CHP, on agricultural fire frequency. I added weather control variables in columns (2) and (5), and multiple fixed effects in columns (3) and (6). Weather controls include average temperature, precipitation, humidity, wind speed, and sunshine duration. Standard errors in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1.

findings are consistent with recent studies (e.g., Weng et al., 2024), which also report significant reductions in pollutant levels attributed to CHP implementation using multidimensional fixed-effect DID models. Overall, the empirical evidence suggests that the CHP has contributed to lower emissions from coal-based heating and incremental improvements in ambient air quality, reinforcing its relevance in the context of energy transition and environmental policy evaluation.

The Clean Heating Policy (CHP) is associated with an estimated 4.8% reduction in $PM_{2.5}$ concentrations. While this reduction appears modest in relative terms, epidemiological literature indicates that even small improvements in air quality can translate into substantial public health benefits. In the context of China, Chen et al. (2013) report that a 10 μg/m^3 decline in $PM_{2.5}$ is linked to an increase of approximately 0.6 years in life expectancy. In the United States, Pope et al. (2009) estimate a 6%–15% reduction in cardiopulmonary mortality for every 10 μg/m^3 decrease in $PM_{2.5}$, and Di et al. (2017) find significant reductions in all-cause mortality among elderly populations. European evidence from Cesaroni et al. (2013) suggests that a 5 μg/m^3 decline is associated with a 7% drop in natural mortality risk. Taken together, these findings imply that even moderate air quality improvements—such as those associated with the CHP—could yield measurable reductions in health-related risks at the population level.

The results reported in Columns (4) to (6) show that the Clean Heating Policy (CHP) is associated not only with improved air quality but also with a statistically significant reduction in agricultural fire frequency. In the baseline specification without additional controls, the policy's suppressive effect on agricultural fires is statistically significant at conventional levels. When weather-related control variables are introduced in Column (5), the estimated coefficient slightly increases in magnitude, although the change is modest compared to the variation observed in $PM_{2.5}$ concentrations. This pattern is consistent with the view that agricultural fire occurrences are primarily influenced by human activities and are comparatively less sensitive to meteorological fluctuations, as documented in prior research (Liu et al., 2025).

This inference aligns with the primary causes of agricultural fires—farmers typically burn crop residues to clear fields, enhance soil fertility, or, in some regions, as a supplementary source of rural heating fuel. Therefore, the frequency of such fires is more closely associated with agricultural production activities and rural energy supply conditions, rather than short-term weather fluctuations (Ren et al., 2019). After further introducing multidimensional fixed effects in Column (6), the regression results become stable and remain highly statistically significant, reinforcing the robustness of the CHP's governance effect. Referring to the descriptive statistics in Table 1, the probability of agricultural fires decreases by approximately 17.4% following the implementation of the CHP (−7.048 fires relative to a mean of 75.526). This result suggests that the promotion of clean heating has significantly reduced farmers' dependence on crop residue burning, thereby facilitating rural energy transition while mitigating the environmental pollution and safety risks associated with straw burning. This conclusion is consistent with the findings of Liu et al. (2024) and Nie et al. (2023), both of which confirm that the Clean Heating Policy exhibits significant environmental spillover effects, particularly in reducing agricultural fires and improving rural energy structures.

This pattern is consistent with the commonly recognized causes of agricultural fires, as farmers typically burn crop residues to clear fields, enhance soil fertility, or—as observed in some regions—use them as supplementary rural heating fuel. Consequently, the frequency of such fires appears to be more strongly correlated with agricultural production practices and rural energy supply conditions, rather than short-term meteorological variations (Ren et al., 2022). After incorporating multidimensional fixed effects in Column (6), the estimation results remain stable and statistically significant, supporting the robustness of the CHP's estimated governance effect. Referring to the descriptive statistics in Table 1, the probability of agricultural fires declines by approximately 17.4% following policy implementation (−7.048 fires relative to a mean of 75.526). This effect indicates that the promotion of clean heating may have reduced reliance on crop residue burning, thereby facilitating a gradual rural energy transition and contributing to the mitigation of environmental and safety risks associated with open-field burning. These findings are in line with prior studies (Liu et al., 2024; Nie et al., 2023), which also document significant environmental spillover benefits of the CHP, particularly in terms of reducing agricultural fire occurrences and improving rural energy structure.

5.3 Robustness checks

5.3.1 Parallel trend test

A core identifying assumption of the Difference-in-Differences (DID) framework is that, in the absence of treatment, the outcomes for treated and untreated units would have followed parallel trends. This assumption is essential for causal inference in DID applications, particularly under staggered treatment adoption and heterogeneous effects (Autor, 2003; Sun and Abraham, 2021). In this context, the plausibility of the parallel trends assumption is supported by both the institutional design of the policy and the observed data patterns. The Clean Heating Policy (CHP) was implemented through a centrally coordinated, phased rollout process in which the inclusion and timing of local jurisdictions were determined primarily by top-down administrative criteria, rather than local pollution levels or economic fluctuations. This exogenous assignment mechanism helps mitigate concerns about endogenous selection into treatment groups and strengthens the credibility of the identifying assumption.

To empirically assess the plausibility of the parallel trends assumption, an event-study specification is estimated based on Equation 2, using the pre-policy years as the reference period. The dynamic treatment effects are illustrated in Figure 1. Panel (a) presents the estimated effects of the CHP on $PM_{2.5}$ concentrations. During the pre-treatment period (2012–2013), the coefficients are statistically indistinguishable from zero, and a joint F-test does not reject the null hypothesis of no anticipatory policy effects ($p > 0.1$). Following policy implementation, post-treatment estimates are consistently negative and statistically significant, a pattern that is consistent with a sustained decline in $PM_{2.5}$ concentrations (Xin et al., 2025). Panel (b) displays similar post-treatment dynamics for agricultural fire frequency, though with an apparent 1-year delay, which may reflect the seasonal nature of crop residue burning and gradual behavioral adjustments among rural households.

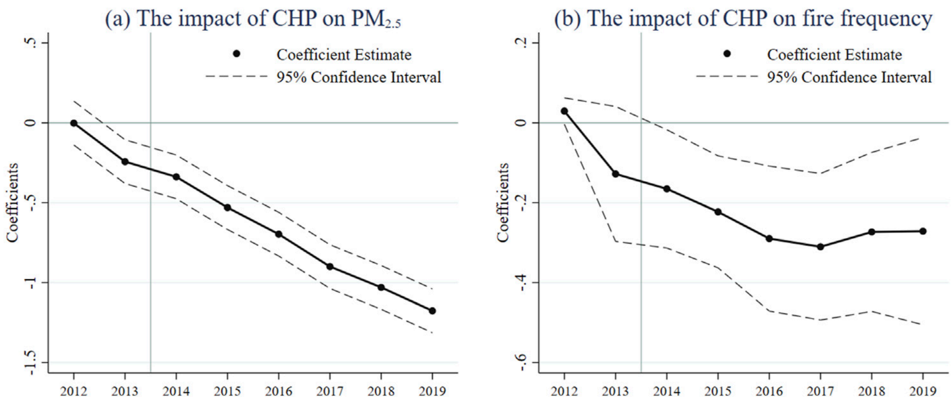

FIGURE 1
Parallel trend test. **(a)** The impact of the Clean Heating Policy (CHP) on PM_{2-5} concentrations. **(b)** The impact of the Clean Heating Policy (CHP) on agricultural fire frequency. The solid dots represent coefficient estimates, and the dashed lines indicate the 95% confidence intervals.

TABLE 3 Robustness checks - The effect of CHP on other pollutants.

Variables	(1)	(2)	(3)	(4)	(5)
	PM_{10} (μg/m³)	SO_2 (μg/m³)	NO_2(μg/m³)	CO (mg/m³)	O_3 (μg/m³)
CHP	−2.470*** (0.133)	−0.845*** (0.061)	−1.233*** (0.343)	−0.028*** (0.004)	−0.038 (0.029)
Weather controls	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes	Yes	Yes
R-squared	0.567	0.348	0.391	0.327	0.391
Observations	12, 597	12, 597	12, 597	12, 597	12, 597

Note: This table reports robustness checks using five alternative air pollutant indicators as dependent variables. All models include weather controls, year, county, and province-year fixed effects. Standard errors are clustered at the county level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. Standard errors in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1.

The use of event-study specifications in staggered Difference-in-Differences (DID) settings provides a flexible framework for evaluating identification assumptions, enabling both graphical and statistical assessment of dynamic treatment effects. Although recent methodological literature has raised concerns regarding treatment effect heterogeneity and negative weighting in traditional two-way fixed effects models (Goodman-Bacon, 2021; De Chaisemartin and d'Haultfoeuille, 2020), the combination of non-significant pre-treatment trends, institutional exogeneity in policy rollout, and stable post-treatment dynamics observed in this study supports the plausibility of the identifying assumptions. Such validation is particularly important given the staggered, multi-year implementation of the Clean Heating Policy, and supports the robustness of the estimated treatment effects reported in the subsequent empirical sections.

5.3.2 The impact on other pollutants

The impact of the Clean Heating Policy (CHP) on other common air pollutants was also examined, and the estimation results are presented in Table 3. The findings suggest that the policy is associated not only with reductions in $PM_{2.5}$ concentrations but also with statistically significant decreases in levels of PM_{10}, SO_2, NO_2, and CO. These results imply that the CHP may support the broader control of multiple air pollutants through reduced emissions from coal-based heating, thereby contributing to a more comprehensive improvement in ambient air quality.

From the perspective of specific policy directives, local governments receiving clean heating targets from higher-level authorities have been observed to implement regionally adapted financial subsidies and technical support based on local infrastructure and energy profiles. For instance, subsidies have been provided to support the upgrading of household heating systems, encouraging the replacement of traditional coal-based heating with cleaner alternatives such as natural gas, electricity, or geothermal energy. According to the Plan for Clean Heating in Northern China in Winter (2017–2021) and related policy documents, "coal-to-gas" and "coal-to-electricity" initiatives have been prioritized, with several regions offering targeted subsidies for equipment purchases (e.g., gas-fired wall-hung boilers, electric heating units) and preferential energy pricing during the heating season to reduce costs.

Furthermore, documents such as the Comprehensive Work Plan for Energy Conservation and Emission Reduction during the 14th Five-Year Plan and the Action Plan for Carbon Peaking Before 2030 explicitly emphasize the expansion of renewable energy

TABLE 4 Robustness checks - The effect of CHP on fire frequency on different confidence intervals.

Variables	(1)	(2)	(3)	(4)	(5)
	Fire frequency (CI)				
	>20%	>30%	>40%	>50%	>60%
CHP	−7.354*** (0.342)	−6.529*** (0.349)	−6.795*** (2.220)	−5.228*** (1.900)	−4.977*** (1.693)
Weather controls	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes	Yes	Yes
R-squared	0.563	0.578	0.563	0.665	0.784
Observations	12, 597	12, 597	12, 597	12, 597	12, 597

Note: This table reports robustness checks of the CHP, effect on fire frequency using alternative confidence interval (CI) thresholds. All models include weather controls, year, county, and province-year fixed effects. Standard errors are clustered at the county level. Standard errors in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1.

heating systems and the optimization of subsidy mechanisms to enhance long-term policy sustainability. These policy measures, through financial incentives and technical assistance, appear to support the transition toward cleaner household heating and are associated with reductions in multiple air pollutants. In addition to environmental benefits, such initiatives may also contribute to energy restructuring and the advancement of low-carbon development objectives.

5.3.3 Verification of the credibility of a fire point

5.3.3.1 Exclude the influence of the confidence interval of the fire point location

To ensure the robustness of the regression results, a verification step is conducted to address potential bias arising from the confidence intervals of fire point detection. Specifically, the fire point dataset is reprocessed using alternative confidence thresholds, and the regression models are re-estimated accordingly. The results are reported in Table 4. In Column (1), fire points with confidence levels below 20% are excluded. The estimated coefficients remain highly consistent with the baseline results in Table 2, suggesting that potential measurement errors associated with low-confidence fire points may exert only limited influence on the estimation. This finding is consistent with Engel et al. (2021), who report that fire point detection uncertainty at low confidence levels has minimal impact on empirical identification.

Subsequently, the confidence threshold is progressively increased to further reduce potential biases associated with satellite-based fire point misclassification. The threshold is raised in increments up to 60%. Although the regression coefficients decrease slightly with stricter filtering, they remain negative and statistically significant across all specifications, which supports the robustness of the Clean Heating Policy's (CHP) estimated suppressive effect on agricultural fire activity. This result is consistent with Ying et al. (2019), who suggest that higher confidence thresholds in fire point identification reduce misclassification errors stemming from surface reflectance, cloud cover, and other environmental interferences, thereby supporting the credibility of such robustness checks in satellite-based fire detection studies.

5.3.3.2 Exclude the potential impacts of cloudy and rainy weather

The Moderate Resolution Imaging Spectroradiometer (MODIS), as part of NASA's Earth Observing System, provides all-weather global monitoring and is widely applied in fire detection research. However, its fire point identification accuracy can be affected by environmental factors such as cloud cover and precipitation, potentially leading to classification errors (Gong et al., 2021). To mitigate such potential bias, daily observations with cloud cover and precipitation levels exceeding the local historical average were excluded, and the cleaned dataset was then aggregated to the annual level for regression analysis. As reported in Table 5, the estimated coefficients remain consistent with baseline results, suggesting that the main findings are not driven by weather-related misclassification. Given that straw burning predominantly occurs under dry conditions, this refinement may improve the reliability of fire point identification in the context of satellite-based detection (Hu et al., 2021).

Columns (3) and (4) of Table 5 show that the estimated suppressive effect of the Clean Heating Policy (CHP) on agricultural fires is more pronounced under clear weather conditions. This pattern may reflect two underlying factors. First, clear weather is generally associated with dry conditions, which heighten fire risk. Under such circumstances, reduced reliance on coal and straw combustion may contribute more substantially to lowering the incidence of human-induced fires. Second, reduced cloud cover during clear weather improves the accuracy of MODIS fire point detection, thereby minimizing misclassification and enhancing the visibility of policy effects in the data (Dong et al., 2022; Xie et al., 2016). Overall, after removing samples from cloudy and rainy days, the estimated effects of the CHP on both air quality and fire frequency become stronger, which supports the robustness and reliability of the empirical findings.

5.4 Heterogeneity analysis

To further examine the regional heterogeneity in the impact of the Clean Heating Policy (CHP), a subgroup analysis is conducted

TABLE 5 Robustness test - exclude cloudy and rainy day samples.

Variables	(1)	(2)	(3)	(4)
	$PM_{2.5}$		Fire frequency	
CHP	−4.872*** (0.971)	−3.610** (0.778)	−11.146*** (2.314)	−10.621*** (2.574)
Weather controls	No	Yes	No	Yes
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes	Yes
R-squared	0.569	0.594	0.631	0.866
Observations	12, 597	12, 597	12, 597	12, 597

Note: This table reports robustness tests excluding observations from cloudy and rainy days to account for potential weather-related measurement bias. All models include year, county, and province-year fixed effects. Standard errors are clustered at the county level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

TABLE 6 Heterogeneity test - whether it is located in a major grain-producing region.

Variables	(1)	(2)	(3)	(4)
	$PM_{2.5}$	Fire frequency	$PM_{2.5}$	Fire frequency
Panel A	Major grain producing areas		Non-major grain producing areas	
CHP	−2.238*** (0.490)	−9.046*** (3.526)	−1.977*** (0.069)	−6.665*** (1.135)
R-squared	0.378	0.532	0.494	0.576
Observations	2,026	2,026	10,571	10,571
Panel B	Resource-based areas		Non-resource-based areas	
CHP	−1.076** (0.505)	6.812*** (0.613)	−3.365*** (1.114)	−11.426*** (1.657)
R-squared	0.599	0.686	0.511	0.633
Observations	6,786	6,786	5,811	5,811
Weather controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes	Yes

Note: This table reports heterogeneity tests of the CHP, effects. Panel A splits the sample by whether the county is located in a major grain-producing area. Panel B distinguishes counties based on whether they are part of resource-based cities, as defined by the National Development and Reform Commission. all models include weather controls, year, county, and province-year fixed effects. Standard errors are clustered at the county level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

based on whether a county qualifies as a major grain-producing area. Following the classification criteria established by China's Ministry of Agriculture, counties with grain output exceeding 20 million tons for five consecutive years are identified as major grain-producing areas. Specifically, if any of a county's six primary grain crops meets this threshold, the county is categorized as major-producing; otherwise, it is classified as non-major.

The rationale for this classification is grounded in the observed seasonal correlation between grain harvesting cycles and agricultural fire activity. Fire occurrences tend to be more concentrated in major grain-producing counties, where large-scale straw burning is more prevalent. These regions are also generally characterized by higher reliance on traditional heating methods, such as coal and crop residue combustion, which may heighten their responsiveness to clean heating interventions. By comparing counties with varying levels of agricultural intensity, the analysis aims to assess whether the effectiveness of the Clean Heating Policy (CHP) differs in relation to underlying rural energy usage patterns. The corresponding regression results are presented in Table 6, Panel A.

As shown in Table 6, Panel A, a comparison between Columns (1) and (3), as well as Columns (2) and (4), suggests that the estimated policy effects are more substantial in major grain-producing areas. In particular, the Clean Heating Policy (CHP) is associated with a greater reduction in both $PM_{2.5}$ concentrations and agricultural fire frequency in these counties. This pattern may reflect the stronger dependence on straw burning and traditional heating fuels in grain-dominant regions, which increases the potential for measurable improvements when cleaner alternatives are introduced.

Several contextual factors may contribute to the observed heterogeneity. First, major grain-producing areas are typically characterized by more intensive agricultural activity, where the prevalence of crop residue burning is relatively high. The availability of cleaner energy alternatives under the Clean Heating Policy (CHP) may have a greater displacement effect in such settings, potentially contributing to observable improvements in environmental indicators (Li et al., 2020). Second, as key regions for national food security, these areas often receive heightened policy attention, including larger-scale fiscal support and stronger regulatory enforcement, which may facilitate more consistent policy execution. Third, due to relatively high winter heating demand in these regions, the baseline potential for substituting coal and straw-based fuels is also greater, possibly amplifying the measurable effects of the CHP (Wang H. et al., 2024).

To assess regional heterogeneity in policy effects from an urban industrial structure perspective, counties are further classified based on whether their corresponding cities fall under the category of resource-based cities, as defined by the National Plan for the Sustainable Development of Resource-Based Cities (2013–2020) issued by the National Development and Reform Commission. Accordingly, the sample is partitioned into two subgroups—resource-based and non-resource-based cities—and regression analyses are conducted separately.

The motivation for this distinction lies in the structural differences in energy systems and economic composition between resource-based and non-resource-based cities. Resource-based cities often exhibit higher reliance on fossil fuel industries, particularly coal, and may have more entrenched heating infrastructures or local resistance to clean energy transitions. In contrast, non-resource-based cities are more likely to adopt flexible, diversified heating solutions and respond more efficiently to policy incentives. This categorization allows for identification of differential policy effectiveness across industrial and institutional contexts. The results are presented in Table 6, Panel B.

The regression estimates indicate that the Clean Heating Policy (CHP) is associated with reductions in both air pollution and agricultural fire frequency, with variation across urban industrial structures. In resource-based areas, the estimated reduction in $PM_{2.5}$ concentrations is 1.076 μg/m^3, while the corresponding reduction in non-resource-based areas reaches 3.365 μg/m^3. For agricultural fires, the decline is 6.812 units in resource-based cities, compared to 11.426 units in non-resource-based cities. These differences suggest that the measurable impacts of the CHP are larger in non-resource-based areas, potentially reflecting differences in baseline energy structures, implementation capacity, or population density.

One possible explanation for these differences is that non-resource-based cities may exhibit more diversified industrial structures, lower dependence on fossil fuels, and relatively better access to clean energy infrastructure, such as gas distribution networks and electricity grids. These conditions may facilitate more favorable implementation environments and greater responsiveness to clean heating initiatives. In contrast, resource-based cities are often characterized by stronger historical reliance on coal-intensive sectors, limited fiscal resources, and institutional inertia that may constrain the pace of energy transitions. Additionally, the opportunity cost of shifting away from coal and biomass may be higher in these regions, potentially contributing to the relatively weaker observed effects (Lee C. C. et al., 2024; Yang et al., 2022). These structural and administrative constraints may partly account for the regional variation in estimated impacts.

Overall, the heterogeneity analysis demonstrates that the CHP delivers stronger governance effects in major grain-producing areas and non-resource-based cities. This suggests that regions with intensive agricultural activity and lower dependence on fossil resources are more responsive to clean heating interventions, reflecting both environmental urgency and greater institutional capacity for low-carbon transitions.

5.5 Identification of spillover effects

To assess the spatial extent of the Clean Heating Policy (CHP)'s influence, potential spillover effects are examined across varying geographic distances. Specifically, air pollution levels and fire frequencies are measured in neighboring counties located within 10 km, 50 km, and 100 km of treated counties, following the approach outlined by He Y. et al. (2025). This strategy allows for the evaluation of potential cross-regional externalities associated with CHP implementation. The corresponding results are presented in Table 7.

As indicated in Column (2) of Table 7, after controlling for weather-related variables and multidimensional fixed effects, the Clean Heating Policy (CHP) is associated with a statistically significant reduction in $PM_{2.5}$ concentrations in neighboring counties within a 10 km radius. The estimated decline is 3.406 μg/m^3, which exceeds the direct treatment effect observed in the implementing counties. This pattern may reflect implementation synergies among geographically adjacent counties, including shared infrastructure for clean energy supply, cross-regional energy scheduling, or overlapping fiscal subsidy spillovers (He S. et al., 2025).

As geographic distance increases, the estimated spillover effect declines. Within a 50 km radius, a significant but attenuated reduction in air pollution is still observed, with the coefficient approximately one-third the magnitude of the 10 km result. Beyond 100 km, no statistically significant spillover is detected, suggesting that the policy's spatial externalities are geographically limited. This attenuation may be attributable to the reach of clean energy networks, administrative coordination frictions, or regional differences in heating technologies and adoption rates—a conclusion that is consistent with prior studies (Wang F. et al., 2024).

Meanwhile, as shown in Column (4) of Table 7, the suppressive effect of the Clean Heating Policy (CHP) on agricultural fire activity exhibits a broader spatial range than that observed for air pollution. While the reduction in $PM_{2.5}$ concentrations is statistically significant only within 50 km, significant declines in agricultural fire frequency are detected at distances of up to 100 km, suggesting that the policy's influence on fire-related outcomes extends well beyond directly treated counties.

This wider spillover may be driven by two factors. First, by increasing access to clean heating alternatives, the CHP may reduce reliance on crop residue combustion, thereby encouraging adjacent counties to adopt more sustainable disposal practices (Cao et al., 2025). Second, the policy is frequently accompanied by enhanced

TABLE 7 Spatial spillover effect of coal-to-gas policy (CTG) on air pollution and fire frequency.

Variables	(1)	(2)	(3)	(4)
	$PM_{2.5}$		Fire frequency	
CHP_{10km}	−3.237* (1.871)	−3.406* (1.764)	−9.891*** (2.203)	−9.674*** (2.146)
CHP_{50km}	−1.594*** (0.326)	−1.251*** (0.308)	−2.279*** (0.382)	−2.219*** (0.3773)
CHP_{100km}	−0.009 (0.016)	−0.238 0.159	−1.963*** (0.171)	−1.925*** (0.168)
Weather controls	No	Yes	No	Yes
Year FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Province-year FE	Yes	Yes	Yes	Yes
R-squared	0.425	0.432	0.616	0.642
Observations	8,493	8,493	8,493	8,493

Note: This table examines the spatial spillover effects of the Clean Heating Policy (CHP) on $PM_{2.5}$ concentrations and fire frequency at different distance thresholds (10 km, 50 km, and 100 km) from treated counties. All regressions include year, county, and province-year fixed effects. Standard errors are clustered at the county level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

enforcement of straw burning regulations and the promotion of integrated reuse strategies—such as straw collection, biomass energy conversion, and feedstock processing—which may be coordinated at the regional level (Fu et al., 2022). Nevertheless, the estimated coefficients exhibit a declining pattern as distance increases, indicating that the strength of cross-regional policy influence diminishes with geographic separation.

Overall, the spatial spillover effects of the Clean Heating Policy (CHP) exhibit notable divergence across two environmental dimensions. While air pollution mitigation appears to be spatially bounded within a 50 km radius, the reduction in agricultural fire frequency extends to distances of up to 100 km. This discrepancy may reflect differences in the spatial reach of supporting energy infrastructure, the strength of intergovernmental coordination, regional heating practices, and the spatial distribution of agricultural activities. Previous research has highlighted that spillover effects from regional environmental policies often display heterogeneity due to variation in institutional enforcement capacity, cross-jurisdictional collaboration, and the allocation of shared resources (Meng, 2022). These findings underscore the importance of enhancing cross-regional governance arrangements to improve the consistency and geographic coverage of clean heating outcomes.

5.6 Welfare analysis

The Clean Heating Policy (CHP), while reducing air pollution, has also generated significant socio-economic benefits. From a cost-benefit perspective, the primary economic gains of the policy are reflected in three key areas: air pollution mitigation, improvements in public health, and spillover effects.

First, the economic benefits of air pollution control are considerable. According to data from China's Ministry of Ecology and Environment, every 10 μg/m^3 reduction in $PM_{2.5}$ concentration can reduce air pollution-related mortality by approximately 3.1% nationwide. The implementation of the CHP has already achieved reductions of 5–10 μg/m^3 in $PM_{2.5}$ levels across multiple cities (Weng et al., 2021). The World Bank estimates that the health and economic costs associated with air pollution account for approximately 6.6% of China's GDP. By lowering pollution levels, the CHP reduces healthcare expenditures and productivity losses, thereby delivering substantial economic returns. Moreover, the promotion of clean heating reduces coal consumption and encourages the use of natural gas, electricity, and renewable energy, fostering the development of the clean energy industry. For instance, in Beijing, between 2017 and 2021, the "coal-to-gas" and "coal-to-electricity" programs cumulatively reduced coal consumption by approximately 30 million tons, equivalent to a reduction of 75 million tons of CO_2 emissions, significantly improving regional environmental quality (Wu et al., 2023).

Based on the mortality elasticity reported by He et al. (2020), a 10 μg/m^3 decrease in $PM_{2.5}$ corresponds to approximately 2.2 fewer deaths per 10,000 individuals annually. Applying this to a conservative 5 μg/m^3 reduction, and assuming an average population of 500,000 per treated county, this implies around 110 avoided deaths per year. Monetizing this with a Value of Statistical Life (VSL) of 3 million RMB suggests a total health benefit exceeding 300 million RMB annually per county—an amount that substantially reinforces the policy's economic rationale.

Moreover, the promotion of clean heating reduces coal consumption and encourages the use of natural gas, electricity, and renewable energy, fostering the development of the clean energy industry. For instance, in Beijing, between 2017 and 2021, the "coal-to-gas" and "coal-to-electricity" programs cumulatively reduced coal consumption by approximately 30 million tons, equivalent to a reduction of 75 million tons of CO_2 emissions, significantly improving regional environmental quality (Nie et al., 2023). Using a conservative social cost of carbon (SCC) of $50 per ton CO_2 (Greenstone et al., 2013), this reduction translates into a climate-related economic benefit of approximately $3.75 billion (≈27 billion RMB). These carbon-related gains provide a measurable environmental externality benefit that complements the public health improvements.

Second, the improvement in public health represents a critical long-term return of the CHP. Empirical studies have demonstrated that prolonged exposure to high concentrations of $PM_{2.5}$ significantly increases the risk of respiratory diseases, cardiovascular diseases, and cancer. According to related research, air pollution contributed to nearly 1.2 million premature deaths in China in 2019 (Zhao et al., 2018). The CHP has effectively helped reduce this figure, particularly during the high-pollution winter periods in northern regions. For example, following the implementation of the "coal-to-gas" policy in Hebei Province, the rate of winter respiratory disease visits decreased by approximately 15% (Li et al., 2022). Additionally, the reduction in smoke pollution from agricultural fires further lowered respiratory disease incidence in rural areas. Research by Meng et al. (2019) further confirms that the promotion of clean heating in northern rural areas has significantly enhanced local public health levels, providing long-term health improvements for residents.

Lastly, the spillover effects of the CHP are equally noteworthy. The policy not only improved local air quality but also had significant positive impacts on surrounding areas within a 50–100 km radius. This is particularly evident in major grain-producing regions, where reduced straw burning curbed pollution dispersion and improved regional environmental quality (He et al., 2016). At the same time, the expansion of clean energy infrastructure stimulated regional economic development. For example, in 2020, the Chinese government allocated approximately 50 billion yuan in fiscal subsidies for clean heating, which attracted over 200 billion yuan in social investment, creating a strong leverage effect (Wang F. et al., 2024). This process not only facilitated the growth of the renewable energy industry but also generated numerous employment opportunities, further enhancing the comprehensive socio-economic benefits of the CHP.

In summary, although the CHP requires substantial fiscal investment in the short term, its long-term economic returns far outweigh the costs, particularly in the areas of air pollution control, public health improvement, and regional economic development. Therefore, future policy efforts should focus on optimizing subsidy mechanisms, refining energy pricing systems, and strengthening inter-regional governance cooperation to improve policy efficiency and maximize broader social welfare outcomes.

6 Conclusion and policy implications

In recent years, air pollution mitigation and clean energy transition have emerged as central priorities on both global and national policy agendas. As the world's largest developing economy and one of the top energy consumers, China confronts severe environmental challenges driven by coal-intensive winter heating practices. These practices contribute not only to persistently elevated $PM_{2.5}$ concentrations but also to widespread agricultural fire activity associated with straw burning in rural areas. In response to these interrelated environmental and public health concerns, the Chinese government initiated the Clean Heating Policy (CHP) in 2013, aiming to accelerate coal substitution through structural energy reform and the modernization of rural heating systems.

This study systematically evaluates the environmental effectiveness of the Clean Heating Policy (CHP) by combining high-resolution, multi-source satellite remote sensing data with a staggered Difference-in-Differences (DID) framework. The analysis centers on three dimensions: the policy's impact on ambient $PM_{2.5}$ concentrations, its effectiveness in reducing agricultural fire frequency, and the spatial extent of spillover effects into neighboring regions. This integrated approach provides robust empirical evidence to inform the refinement and regional tailoring of future clean energy transition policies.

The empirical findings indicate that the Clean Heating Policy (CHP) has generated substantial governance outcomes across multiple dimensions. First, the policy is associated with a statistically significant reduction in air pollutant concentrations, particularly $PM_{2.5}$, with an initial decline of 5.55 $\mu g/m^3$ before covariate adjustment and a stabilized reduction of approximately 4.8% after controlling for weather variables and fixed effects. Notable spatial spillover effects are also observed: within a 10 km radius, $PM_{2.5}$ concentrations decline by an average of 3.406 $\mu g/m^3$. However, the magnitude of the spillover decreases at 50 km and becomes statistically insignificant at 100 km.

Second, the CHP appears to substantially reduce agricultural fire activity, with fire frequency declining by 17.4% in the year following policy implementation. This effect remains significant within a 100 km range, likely reflecting enhanced enforcement of straw burning regulations and behavioral adaptation among rural households.

Finally, heterogeneity analysis suggests that the policy's environmental effects are more pronounced in major grain-producing areas, where both air quality improvements and fire suppression are greater. These results highlight the amplified benefits of clean heating interventions in regions characterized by intensive agricultural activity and higher baseline pollution levels.

Based on these findings, several targeted policy implications are proposed. First, the government should adopt geographically differentiated clean heating strategies. In major grain-producing areas—where both pollution levels and biomass burning are higher—clean heating subsidies and infrastructure investment should be prioritized. Region-specific tools, such as income-based tiered subsidies or production-weighted support formulas, can enhance both environmental performance and equity. In contrast, less polluted or agriculturally intensive regions may rely more on behavioral incentives, voluntary programs, or lower-cost technological options.

Second, spatial spillovers underscore the need for inter-regional policy coordination. Localized actions may generate transboundary benefits, particularly within 50 km of treatment zones. Thus, policymakers should consider establishing joint regional councils or shared investment frameworks to synchronize heating plans, reduce policy fragmentation, and internalize spatial externalities.

Third, public awareness remains vital. Complementing infrastructure investment with educational campaigns about health impacts of PM2.5 and the benefits of clean heating can accelerate behavioral adaptation, especially in rural communities with persistent straw burning habits. In parallel, promoting the reuse of agricultural residues—e.g., for biomass energy or composting—can further alleviate environmental pressures.

While these measures provide promising policy directions, their practical feasibility is contingent upon regional disparities in fiscal capacity, infrastructure availability, and administrative implementation capability. Economically disadvantaged regions may require increased central government support, including initial investments in energy infrastructure and sustained operating subsidies. In addition, the effective deployment of clean heating systems relies on stable access to electricity and gas networks, which may be insufficient or fragmented in remote or sparsely populated areas.

To ensure an equitable and effective rollout, future policy design should explicitly account for spatial and socioeconomic heterogeneity. The adoption of tiered subsidy schemes—differentiated by household income, energy demand, or climatic conditions—can enhance distributional fairness. In parallel, the establishment of institutionalized coordination platforms may help to amplify and stabilize regional effects. Overall, the Clean Heating Policy (CHP) exhibits considerable potential in improving air quality and mitigating environmental risks. Its future refinement should prioritize precision targeting, fiscal sustainability, and mechanisms for interjurisdictional cooperation.

While this study offers robust evidence on the environmental effectiveness of the Clean Heating Policy, several aspects merit further exploration. First, the analysis relies on remotely sensed and administrative datasets aggregated at the county level, which, although appropriate for macro-level policy evaluation, may not fully capture micro-level behavioral responses or short-term policy adjustments. Second, this study focuses primarily on air quality and fire frequency outcomes, while other important co-benefits—such as reductions in carbon emissions or improvements in public health—are not quantitatively assessed due to data constraints. These effects are likely to be substantial and warrant further investigation. Future research could integrate individual- or household-level survey data, health and mortality outcomes, or life-cycle carbon assessments to provide a more comprehensive picture of clean heating transitions and their socio-environmental impacts.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: Clean Heating Policy Data: Collected from the official websites of provincial, municipal, and county-level governments in China. Air Pollution and Fire Frequency Data: Retrieved from NASA's LAADS (Level 1 and Atmosphere Archive and Distribution System) database. Available at: https://ladsweb.modaps.eosdis.nasa.gov/search/order/1/MOD14–6. China Meteorological Historical Data: Sourced from the National Centers for Environmental Information (NCEI) of the U.S. National Climatic Data Center (NCDC). Available at: https://www.ncei.noaa.gov/data/.

Author contributions

XJ: Formal Analysis, Writing – original draft, Funding acquisition, Visualization, Resources, Software, Conceptualization, Methodology, Project administration, Supervision, Data curation, Investigation, Writing – review and editing, Validation.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was funded by BIT Research and Innovation Promoting Project, grant number 2024YCXZ012.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

References

Angrist, J. D., and Krueger, A. B. (1999). Empirical strategies in labor economics. *Handb. labor Econ.* 3, 1277–1366. doi:10.1016/s1573-4463(99)03004-7

Autor, D. H. (2003). Outsourcing at will: the contribution of unjust dismissal doctrine to the growth of employment outsourcing. *J. labor Econ.* 21 (1), 1–42. doi:10.1086/344122

Beck, T., Levine, R., and Levkov, A. (2010). Big bad banks? The winners and losers from bank deregulation in the United States. *J. finance* 65 (5), 1637–1667. doi:10.1111/j.1540-6261.2010.01589.x

Bertrand, M., Duflo, E., and Mullainathan, S. (2004). How much should we trust differences-in-differences estimates? *Q. J. Econ.* 119 (1), 249–275. doi:10.1162/003355304772839588

Callaway, B., and Sant'Anna, P. H. (2021). Difference-in-differences with multiple time periods. *J. Econ.* 225 (2), 200–230. doi:10.1016/j.jeconom.2020.12.0

Cao, J., Liu, T. X., Ma, R., and Sun, A. (2025). Antisocial responses to the "coal to gas" regulation: an unintended consequence of a residential energy policy. *Manag. Sci.* doi:10.1287/mnsc.2023.01459

Cesaroni, G., Badaloni, C., Gariazzo, C., Stafoggia, M., Sozzi, R., Davoli, M., et al. (2013). Long-term exposure to urban air pollution and mortality in a cohort of more than a million adults in Rome. *Environ. health Perspect.* 121 (3), 324–331. doi:10.1289/ehp.1205862

Chen, J., Luo, W., Ren, X., and Liu, T. (2023). The local-neighborhood effects of low-carbon city pilots program on PM2. 5 in China: a spatial difference-in-differences analysis. *Sci. Total Environ.* 857, 159511. doi:10.1016/j.scitotenv.2022.159511

Chen, J., Shi, X., Zhang, M. A., and Zhang, S. (2024a). Centralization of environmental administration and air pollution: evidence from China. *J. Environ. Econ. Manag.* 126, 103016. doi:10.1016/j.jeem.2024.103016

Chen, S., and Chi, H. (2021). Analysis of the environmental effects of the clean heating policy in Northern China. *Sustainability* 13 (12), 6695. doi:10.3390/su13126695

Chen, W., Hu, S., and Liu, Y. (2025a). Synergistic policy effects of digitization in reducing air pollution and addressing climate change in China. *J. Environ. Manag.* 380, 124730. doi:10.1016/j.jenvman.2025.124730

Chen, Y., Ebenstein, A., Greenstone, M., and Li, H. (2013). Evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River policy. *Proc. Natl. Acad. Sci.* 110 (32), 12936–12941. doi:10.1073/pnas.1300018110

Chen, Y., Li, J., Zhang, Y., and Yang, F. (2025b). Pollution and carbon reduction effects of the pilot policy on clean winter heating in Northern China: evidence from the county level. *Chin. J. Popul. Resour. Environ.* 23 (1), 85–95. doi:10.1016/j.cjpre.2025.01.008

Chen, Y., Peng, K., and Zhao, K. (2024b). The impact of strategic alliances on corporate green innovation: evidence from China. *Rev. Econ. Assess.* 3 (4), 52–69. doi:10.58567/rea03040004

De Chaisemartin, C., and d'Haultfoeuille, X. (2020). Two-way fixed effects estimators with heterogeneous treatment effects. *Am. Econ. Rev.* 110 (9), 2964–2996. doi:10.1257/aer.20181169

Di, Q., Wang, Y., Zanobetti, A., Wang, Y., Koutrakis, P., Choirat, C., et al. (2017). Air pollution and mortality in the Medicare population. *N. Engl. J. Med.* 376 (26), 2513–2522. doi:10.1056/NEJMoa1702747

Dong, Z., Yu, J., An, S., Zhang, J., Li, J., and Xu, D. (2022). Forest fire detection of FY-3D using genetic algorithm and brightness temperature change. *Forests* 13 (6), 963. doi:10.3390/f13060963

Engel, C. B., Jones, S. D., and Reinke, K. J. (2021). Real-time detection of daytime and night-time fire hotspots from geostationary satellites. *Remote Sens.* 13 (9), 1627. doi:10.3390/rs13091627

Fu, J., Song, S., Guo, L., Chen, W., Wang, P., Duanmu, L., et al. (2022). Interprovincial joint prevention and control of open straw burning in Northeast China: implications for atmospheric environment management. *Remote Sens.* 14 (11), 2528. doi:10.3390/rs14112528

Gong, A., Li, J., and Chen, Y. (2021). A spatio-temporal brightness temperature prediction method for forest fire detection with modis data: a case study in san diego. *Remote Sens.* 13 (15), 2900. doi:10.3390/rs13152900

Goodman-Bacon, A. (2021). Difference-in-differences with variation in treatment timing. *J. Econ.* 225 (2), 254–277. doi:10.1016/j.jeconom.2021.03.014

Greenstone, M., Kopits, E., and Wolverton, A. (2013). Developing a social cost of carbon for US regulatory analysis: a methodology and interpretation. *Rev. Environ. Econ. policy* 7, 23–46. doi:10.1093/reep/res015

He, G., Fan, M., and Zhou, M. (2016). The effect of air pollution on mortality in China: evidence from the 2008 Beijing Olympic Games. *J. Environ. Econ. Manag.* 79, 18–39. doi:10.1016/j.jeem.2016.04.004

He, G., Liu, T., and Zhou, M. (2020). Straw burning, PM2. 5, and death: evidence from China. *J. Dev. Econ.* 145, 102468. doi:10.1016/j.jdeveco.2020.102468

He, S., Wu, X., and Wang, J. (2025a). Comprehensive economic impact assessment of regional shipping emissions: a case study of Shanghai, China. *Mar. Pollut. Bull.* 211, 117368. doi:10.1016/j.marpolbul.2024.117368

He, Y., Wang, H., Zheng, Y., Feng, Y., Chen, X., Jin, L., et al. (2025b). Revealing air quality impacts of the clean heating campaign in northern China. *Energy Econ.* 141, 108078. doi:10.1016/j.eneco.2024.108078

Hong, X., Zhang, C., Tian, Y., Wu, H., Zhu, Y., and Liu, C. (2023). Quantification and evaluation of atmospheric emissions from crop residue burning constrained by satellite observations in China during 2016–2020. *Sci. Total Environ.* 865, 161237. doi:10.1016/j.scitotenv.2022.161237

Hu, J., Fu, Y., Zhang, P., Min, Q., Gao, Z., Wu, S., et al. (2021). Satellite retrieval of microwave land surface emissivity under clear and cloudy skies in China using observations from AMSR-E and MODIS. *Remote Sens.* 13 (19), 3980. doi:10.3390/rs13193980

Jiang, L., He, S., Cui, Y., Zhou, H., and Kong, H. (2020). Effects of the socio-economic influencing factors on SO2 pollution in Chinese cities: a spatial econometric analysis based on satellite observed data. *J. Environ. Manag.* 268, 110667. doi:10.1016/j.jenvman.2020.110667

Kloog, I., Koutrakis, P., Coull, B. A., Lee, H. J., and Schwartz, J. (2011). Assessing temporally and spatially resolved PM2. 5 exposures for epidemiological studies using satellite aerosol optical depth measurements. *Atmos. Environ.* 45 (35), 6267–6275. doi:10.1016/j.atmosenv.2011.08.066

Lee, C. C., Du, L., and Wang, C. S. (2024a). Carbon blessing or carbon curse? The role of fiscal policy. *Econ. Analysis Policy* 83, 1097–1114. doi:10.1016/j.eap.2024.08.012

Lee, M., Chang, J., Deng, Q., Hu, P., Bixby, H., Harper, S., et al. (2024b). Effects of a coal to clean heating policy on acute myocardial infarction in Beijing: a difference-in-differences analysis. *Lancet Planet. Health* 8 (11), e924–e932. doi:10.1016/S2542-5196(24)00243-2

Levy, R. C., Remer, L. A., Mattoo, S., Vermote, E. F., and Kaufman, Y. J. (2007). Second-generation operational algorithm: retrieval of aerosol properties over land from inversion of Moderate Resolution Imaging Spectroradiometer spectral reflectance. *J. Geophys. Res. Atmos.* 112 (D13). doi:10.1029/2006JD007811

Li, H., Zhang, L., Chen, T., and Liao, H. (2022). Environmental and health impacts of heating fuel transition: evidence from Northern China. *Energy Build.* 276, 112483. doi:10.1016/j.enbuild.2022.11248

Li, Q., Jiang, J., Wang, S., Rumchev, K., Mead-Hunter, R., Morawska, L., et al. (2017). Impacts of household coal and biomass combustion on indoor and ambient air quality in China: current status and implication. *Sci. Total Environ.* 576, 347–361. doi:10.1016/j.scitotenv.2016.10.080

Li, Y., Yuan, X., Tang, Y., Wang, Q., Ma, Q., Mu, R., et al. (2020). Integrated assessment of the environmental and economic effects of "coal-to-gas conversion" project in rural areas of northern China. *Environ. Sci. Pollut. Res.* 27, 14503–14514. doi:10.1007/s11356-020-08004-y

Lin, C., Shao, S., Sun, W., and Yin, H. (2021). Can the electricity price subsidy policy curb NOX emissions from China's coal-fired power industry? A difference-in-differences approach. *J. Environ. Manag.* 290, 112367. doi:10.1016/j.jenvman.2021.112367

Liu, K., Wu, Q., Ren, Y., and Wang, S. (2022). Air pollutant emissions from residential solid fuel combustion in the Pan-Third Pole region. *Environ. Sci. and Technol.* 56 (22), 15347–15355. doi:10.1021/acs.est.2c04150

Liu, T., He, G., and Lau, A. K. H. (2020). Statistical evidence on the impact of agricultural straw burning on urban air quality in China. *Sci. Total Environ.* 711, 134633. doi:10.1016/j.scitotenv.2019.134633

Liu, W., Cheng, Z., Li, J., Li, G., and Pan, N. (2025). Assessment of ecological asset quality and its drivers in Agro-pastoral Ecotone of China. *Ecol. Indic.* 170, 113072. doi:10.1016/j.ecolind.2025.11307

Liu, X., Liu, J., and Liu, Z. (2024). Developing a model of propagating the straw burning prohibition policy in Chinese rural communities and exploring its countermeasures. *Energy Rep.* 11, 2556–2564. doi:10.1016/j.egyr.2024.02.019

Lu, H., Rissman, J., Swae, N., Tian, Z., and Zhou, N. (2024). Clean industry in China: a techno-economic comparison of electrified heat technologies, barriers, and policy options. *Techincal Rep*. doi:10.20357/B70894

Lv, Z., Shi, Y., Guo, D., Zhu, Y., Man, H., Zhang, Y., et al. (2022). High-resolution daily emission inventory of biomass burning in the Amur-Heilong river basin based on MODIS fire radiative energy data. *Remote Sens.* 14 (16), 4087. doi:10.3390/rs14164087

Ma, Z., Liu, R., Liu, Y., and Bi, J. (2019). Effects of air pollution control policies on $PM_{2.5}$ pollution improvement in China from 2005 to 2017: a satellite-based perspective. *Atmos. Chem. Phys.* 19 (10), 6861–6877. doi:10.5194/acp-19-6861-2019

Meng, W. (2022). Understanding the heterogeneity in the effect of driving restriction policies on air quality: evidence from Chinese cities. *Environ. Resour. Econ.* 82 (1), 133–175. doi:10.1007/s10640-022-00665-2

Meng, W., Zhong, Q., Chen, Y., Shen, H., Yun, X., Smith, K. R., et al. (2019). Energy and air pollution benefits of household fuel policies in northern China. *Proc. Natl. Acad. Sci.* 116 (34), 16773–16780. doi:10.1073/pnas.1904182116

Mortadha, H., Kerrouchi, H. B., Al-Othman, A., and Tawalbeh, M. (2025). A comprehensive review of biomass pellets and their role in sustainable energy: production, properties, environment, economics, and logistics. *Waste Biomass Valorization*, 1–33. doi:10.1007/s12649-024-02873-x

Nie, Y., Deng, M., Shan, M., and Yang, X. (2023). Clean and low-carbon heating in the building sector of China: 10-Year development review and policy implications. *Energy Policy* 179, 113659. doi:10.1016/j.enpol.2023.113659

Peng, Y., Zhao, Y., Gao, N., Sheng, D., Tang, S., Zheng, S., et al. (2025). Spatiotemporal evolution of PM2. 5 and its components and drivers in China, 2000–2023: effects of air pollution prevention and control actions in China. *Environ. Geochem. Health* 47 (3), 69–18. doi:10.1007/s10653-025-02375-2

Pope, C. A., Ezzati, M., and Dockery, D. W. (2009). Fine-particulate air pollution and life expectancy in the United States. *N. Engl. J. Med.* 360 (4), 376–386. doi:10.1056/NEJMsa0805646

Popovski, E., Aydemir, A., Fleiter, T., Bellstädt, D., Büchele, R., and Steinbach, J. (2019). The role and costs of large-scale heat pumps in decarbonising existing district heating networks–A case study for the city of Herten in Germany. *Energy* 180, 918–933. doi:10.1016/j.energy.2019.05.122

Qi, M., Du, W., Zhu, X., Wang, W., Lu, C., Chen, Y., et al. (2019). Fluctuation in time-resolved PM2. 5 from rural households with solid fuel-associated internal emission sources. *Environ. Pollut.* 244, 304–313. doi:10.1016/j.envpol.2018.10.041

Qu, Z., Wang, X., Li, F., Li, Y., Chen, X., and Chen, M. (2020). PM2. 5-related health economic benefits evaluation based on air improvement action plan in Wuhan City, middle China. *Int. J. Environ. Res. public health* 17 (2), 620. doi:10.3390/ijerph17020620

Rehman, H. U., Hirvonen, J., Jokisalo, J., Kosonen, R., and Sirén, K. (2020). EU emission targets of 2050: costs and CO2 emissions comparison of three different solar and heat pump-based community-level district heating systems in nordic conditions. *Energies* 13 (16), 4167. doi:10.3390/en13164167

Ren, H., Gu, G., and Zhou, H. (2022). Assessing the low-carbon city pilot policy on carbon emission from consumption and production in China: how underlying mechanism and spatial spillover effect? *Environ. Sci. Pollut. Res.* 29 (47), 71958–71977. doi:10.1007/s11356-022-21005-3

Ren, J., Yu, P., and Xu, X. (2019). Straw utilization in China—status and recommendations. *Sustainability* 11 (6), 1762. doi:10.3390/su11061762

Shen, G., Xiong, R., Tian, Y., Luo, Z., Jiangtulu, B., Meng, W., et al. (2022). Substantial transition to clean household energy mix in rural China. *Natl. Sci. Rev.* 9 (7), nwac050. doi:10.1093/nsr/nwac050

Sun, L., and Abraham, S. (2021). Estimating dynamic treatment effects in event studies with heterogeneous treatment effects. *J. Econ.* 225 (2), 175–199. doi:10.1016/j.jeconom.2020.09.006

Van Donkelaar, A., Martin, R. V., Brauer, M., Hsu, N. C., Kahn, R. A., Levy, R. C., et al. (2016). Global estimates of fine particulate matter using a combined geophysical-statistical method with information from satellites, models, and monitors. *Environ. Sci. and Technol.* 50 (7), 3762–3772. doi:10.1021/acs.est.5b05833

Waheeb, R., and Kocins, G. (2023). Achieve sustainable development of projects by integrating good risk management and performance evaluation. *Rev. Eco. Assess.* 3 (4), 32–51. doi:10.58567/rea03040003

Wang, F., Cheng, S., Chen, M., and Cheng, S. (2024a). Does sub-provincial fiscal decentralization reform improve energy transition? Evidence from a county-level quasi-natural experiment in China. *J. Clean. Prod.* 481, 144156. doi:10.1016/j.jclepro.2024.14415

Wang, H., Zhou, S., and Zhang, P. (2024b). Clean heating and clean air: evidence from the coal-to-gas program in China. *China Econ. Rev.* 85, 102179. doi:10.1016/j.chieco.2024.10217

Wang, S., Huang, Q., Liu, Q., and Sun, D. (2022). Can clean heating in winter in northern China reduce air pollution? empirical analysis based on the psm-did method. *Energies* 15 (5), 1839. doi:10.3390/en15051839

Weng, Z., Dong, Z., Zhao, Y., Xu, M., Xie, Y., and Lu, F. (2024). Cleaner heating policies contribute significantly to health benefits and cost-savings: a case study in Beijing, China. *Iscience* 27 (7), 110249. doi:10.1016/j.isci.2024.110249

Weng, Z., Han, E., Wu, Y., Shi, L., Ma, Z., and Liu, T. (2021). Environmental and economic impacts of transitioning to cleaner heating in Northern China. *Resour. Conservation Recycl.* 172, 105673. doi:10.1016/j.resconrec.2021.105673

Weng, Z., Wang, Y., Yang, X., Cheng, C., Tan, X., and Shi, L. (2022). Effect of cleaner residential heating policy on air pollution: a case study in Shandong Province, China. *J. Environ. Manag.* 311, 114847. doi:10.1016/j.jenvman.2022.114847

Wu, D., Xie, Y., and Liu, D. (2023). Rethinking the complex effects of the clean energy transition on air pollution abatement: evidence from China's coal-to-gas policy. *Energy* 283, 128413. doi:10.1016/j.energy.2023.12841

Wu, R., Dai, H., Geng, Y., Xie, Y., Masui, T., Liu, Z., et al. (2017). Economic impacts from PM2. 5 pollution-related health effects: a case study in Shanghai. *Environ. Sci. and Technol.* 51 (9), 5035–5042. doi:10.1021/acs.est.7b00026

Xie, H., Du, L., Liu, S., Chen, L., Gao, S., Liu, S., et al. (2016). Dynamic monitoring of agricultural fires in China from 2010 to 2014 using MODIS and GlobeLand30 data. *ISPRS Int. J. Geo-Information* 5 (10), 172. doi:10.3390/ijgi5100172

Xin, J., Du, K., Tong, J., and Guan, X. (2025). The impact of new urbanization pilot policies on carbon emissions in China's small and medium-sized cities. *Environ. Res. Commun.* 7, 035005. doi:10.1088/2515-7620/adad41

Xu, Z., Liu, B., Wang, W., Zhang, Z., and Qiu, W. (2024). Assessing the impact of straw burning on PM2. 5 using explainable machine learning: a case study in Heilongjiang Province, China. *Sustainability* 16 (17), 7315. doi:10.3390/su16177315

Xue, W., Wang, L., Li, X., Xu, Q., and Yang, Z. (2025). The impacts of heat-power cogeneration on air pollution: an empirical study based on the measures for the administration of heat-power cogeneration policy in China. *J. Clean. Prod.* 486, 144472. doi:10.1016/j.jclepro.2024.144472

Yang, X., Wang, W., Wu, H., Wang, J., Ran, Q., and Ren, S. (2022). The impact of the new energy demonstration city policy on the green total factor productivity of resource-based cities: empirical evidence from a quasi-natural experiment in China. *J. Environ. Plan. Manag.* 66 (2), 293–326. doi:10.1080/09640568.2021.1988529

Yang, Z., and Ye, L. (2024). Digital economy and energy intensity: the light and dark side. *Rev. Econ. Assess.* 3 (4), 70–92. doi:10.58567/rea03040005

Ying, L., Shen, Z., Yang, M., and Piao, S. (2019). Wildfire detection probability of MODIS fire products under the constraint of environmental factors: a study based on confirmed ground wildfire records. *Remote Sens.* 11 (24), 3031. doi:10.3390/rs11243031

Zeng, J., Bao, R., and McFarland, M. (2022). Clean energy substitution: the effect of transitioning from coal to gas on air pollution. *Energy Econ.* 107, 105816. doi:10.1016/j.eneco.2022.105816

Zhang, J., Wang, W., Gao, L., Deng, Z., and Tian, Y. (2022). Can the Coal-to-Gas/Electricity policy improve air quality in the Beijing–Tianjin–Hebei region? empirical analysis based on the PSM-DID. *Atmosphere* 13 (6), 879. doi:10.3390/atmos13060879

Zhang, Q., Zheng, Y., Tong, D., Shao, M., Wang, S., Zhang, Y., et al. (2019a). Drivers of improved PM2. 5 air quality in China from 2013 to 2017. *Proc. Natl. Acad. Sci.* 116 (49), 24463–24469. doi:10.1073/pnas.1907956116

Zhang, X., Lu, Y., Wang, Q. G., and Qian, X. (2019b). A high-resolution inventory of air pollutant emissions from crop residue burning in China. *Atmos. Environ.* 213, 207–214. doi:10.1016/j.atmosenv.2019.06.009

Zhang, Y., Li, W., and Wu, F. (2020). Does energy transition improve air quality? Evidence derived from China's Winter Clean Heating Pilot (WCHP) project. *Energy* 206, 118130. doi:10.1016/j.energy.2020.11813

Zhao, B., Zheng, H., Wang, S., Smith, K. R., Lu, X., Aunan, K., et al. (2018). Change in household fuels dominates the decrease in PM2. 5 exposure and premature mortality in China in 2005–2015. *Proc. Natl. Acad. Sci.* 115 (49), 12401–12406. doi:10.1073/pnas.1812955115

Zhao, K., Tian, X., Lai, W., and Xu, S. (2024). Agricultural production and air pollution: an investigation on crop straw fires. *Plos one* 19 (5), e0303830. doi:10.1371/journal.pone.0303830

Zheng, B., Tong, D., Li, M., Liu, F., Hong, C., Geng, G., et al. (2018). Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions. *Atmos. Chem. Phys.* 18 (19), 14095–14111. doi:10.5194/acp-18-14095-2018

Zhou, M., Liu, H., Peng, L., Qin, Y., Chen, D., Zhang, L., et al. (2022). Environmental benefits and household costs of clean heating options in northern China. *Nat. Sustain.* 5 (4), 329–338. doi:10.1038/s41893-021-00837-w