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The devil in the air: Air pollution and dementia[☆]

Meng Sun[a], Naibao Zhao[b,*], Emily Yiying Zheng[c]

[a] *Department of Economics, Thompson Rivers University, 805 TRU Way, Kamloops, V2C 0C8, British Columbia, Canada*
[b] *Research Institute of Economics and Management & Survey and Research Center for China Household Finance, Southwestern University of Finance and Economics, No. 55 Guanghuacun Street, Chengdu, 610074, Sichuan, China*
[c] *Shenzhen Finance Institute & School of Management and Economics, The Chinese University of Hong Kong, Shenzhen, 2001 Longxiang Boulevard, Shenzhen, 518172, Guangdong, China*

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ABSTRACT

We study the causal relationship between air pollution and dementia prevalence. Leveraging the strict air pollution regulations implemented during the 2008 Beijing Olympics and employing a Synthetic Difference-in-Differences (SDID) approach, we find that a 1 $\mu g/m^3$ decrease in annual PM_{10} levels corresponds to a 0.82 percentage point reduction in dementia prevalence (equivalent to 2.39% of the mean). Analyses across demographics show a more pronounced impact on vulnerable groups. Moreover, an economic assessment suggests that a 10 $\mu g/m^3$ reduction in China's air pollution in 2010 could generate up to 2.36 billion US dollars in benefits due to a lower dementia prevalence. These results highlight the potential public health gains achievable through air pollution regulations.

1. Introduction

Dementia is the foremost global challenge in 21st-century health and social care (Livingston et al., 2017).[1] A recent report has estimated that more than 55 million people worldwide live with dementia, with over 60% of these individuals living in low- and middle-income countries, and there are nearly 10 million new cases each year. Furthermore, the total estimated worldwide cost of dementia in 2019 was 1.3 trillion US dollars, which represents 1.5% of the global GDP.[2] Unfortunately, there is no cure or medical means available for preventing dementia. Although epidemiological research indicates that lifestyle modifications can lower the risk of dementia (see some recommendations by WHO (2019)), not everyone is capable of making such changes. We still lack population-wide solutions for slowing the progression of dementia.[3]

[☆] The authors are ordered alphabetically and are collectively acknowledged as co-first authors in recognition of their equal contributions to this study. We thank Lihe Xu and Jiee Zhong for their comments and suggestions. We also thank Shiyu Xie for her assistance in summarizing medical literature on dementia. Special thanks to Professor Xiaoguang Chen and Dr. Jing Gao for providing the supplementary data used in our analysis. We are very grateful to Professor Roger H. von Haefen (the editor) and three anonymous referees for their constructive comments that have significantly improved the article. All errors are our own.

[*] Corresponding author.
E-mail addresses: msun@tru.ca (M. Sun), nzhao@swufe.edu.cn (N. Zhao), emilyzheng@cuhk.edu.cn (E.Y. Zheng).

[1] Dementia is the seventh leading cause of death and is a major contributor to disability and dependency among older individuals worldwide. It is a general term used for a set of symptoms that are caused by disorders affecting the brain. Symptoms may include memory loss and difficulties with thinking, problem-solving, or language that are severe enough to reduce a person's ability to perform everyday activities. Alzheimer's disease is the most common type of dementia. Other types of dementia include vascular dementia, dementia with Lewy bodies, and frontotemporal dementia. Dementia mainly affects older people, although there is a growing awareness of cases that start before the age of 65.

[2] For more information about dementia, please refer to WHO Dementia Fact Sheets posted on March 15, 2023.

[3] To tackle this pressing challenge posed by dementia to healthcare systems, communities, and families worldwide, the WHO recognized dementia as a public health priority and developed a Global Action Plan on Dementia in 2017. One of the seven action areas outlined in this plan is the

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Recent insights from Livingston et al. (2020) have included air pollution as a potential modifiable risk factor for dementia. Remarkably, while the relative risk of air pollution (1.1) is lower compared to well-established lifestyle risk factors such as smoking (1.6), hypertension (1.6), or physical inactivity (1.6), its exceptionally high prevalence (75%) surpasses that of other factors.[4] The widespread prevalence of air pollution as a risk factor for dementia, coupled with individuals' limited control over their exposure, emphasizes the importance of exploring its causal impact. If a causal link exists between air pollution and dementia, then improving air quality can serve as a population-wide strategy to prevent or slow dementia. Moreover, the costs of implementing such air quality improvement policies may be recouped through subsequent reductions in healthcare and societal expenses. However, to date, there is very little causal evidence regarding the effects of air pollution on dementia.[5] Therefore, the questions arise: what is the causal impact of air pollution on dementia, and can air pollution regulations effectively impede the progression of dementia?

To explore these questions, we leverage the drastic air pollution regulations implemented around the 2008 Beijing Olympic Games (hereafter referred to as the BOG08), the largest efforts made in human history to control air quality within a short time period (Chen et al., 2013; He et al., 2016). A set of air quality assurance measures, initiated in late 2007, was rigorously enforced as the Chinese government's dedication to maintaining good air quality in Beijing during the BOG08. The regulations were strict and likely exogenous to dementia prevalence and, therefore, can be regarded as a quasi-natural experiment.[6] This context enables us to formulate a research design that tackles endogeneity in air pollution, thereby obtaining quasi-experimental estimates of the impact of air pollution on dementia prevalence by calculating the estimates from the effects of the BOG08 regulations on both air pollution and dementia prevalence in Beijing.

Estimating the causal effect of the BOG08 regulations on air pollution and dementia prevalence in Beijing relies on reliable estimates of counterfactuals for Beijing's air pollution and dementia prevalence in the absence of BOG08 regulations. We apply the Synthetic Difference-in-Differences (SDID) method developed by Arkhangelsky et al. (2021) to compare outcomes in Beijing to those of synthetic counterfactuals constructed from unregulated provinces in the control group. The SDID strategy fits well with our aim as it allows us to include unit fixed effects that capture the important systematic differences in the levels of outcomes between Beijing and the comparison group and strengthens the role of unregulated provinces in the control group that closely resemble Beijing and the role of pre-BOG08 periods that are similar to treatment periods.

We employ two main datasets in our analyses. The first dataset is sourced from the Chinese Ministry of Environmental Protection (MEP). It contains the daily Air Pollution Index (API) and primary pollutants spanning from 2000 to 2012. Since the official Chinese API does not include fine particulate matter ($PM_{2.5}$), and more than 90% of the time, the primary pollutant is particulate matter 10 micrometers or less in diameter (PM_{10}). We use PM_{10} as the air pollution measure. The second dataset comes from the Chinese Longitudinal Healthy Longevity Survey (CLHLS), the world's most extensive collection of centenarians, along with comparable groups encompassing nonagenarians, octogenarians, and individuals aged 65–79. Dementia is measured by the Mini-Mental State Examination (MMSE) score in the CLHLS.

Our main results are as follows. First, we show that the BOG08 regulations have a positive effect on Beijing's air quality improvement. Specifically, our estimate indicates that the drastic BOG08 air pollution regulations in Beijing significantly reduce PM_{10} concentrations by approximately 26 $\mu g/m^3$ in our baseline regression, consistent with He et al. (2016)'s estimate. We further implement the same estimation of the effect of the BOG08 regulations on dementia prevalence and find that the BOG08 air pollution regulations significantly reduce Beijing's dementia prevalence by 21.7 percentage points. Taken together, these findings indicate that a 1 $\mu g/m^3$ reduction in yearly PM_{10} concentrations reduces the prevalence of dementia in Beijing by 0.82 percentage points, which is 2.39% of the mean prevalence.

Next, we explore the heterogeneity in the effects of air quality improvement on the prevalence of dementia across various subgroups. We find that gender, age, and education play crucial roles. Specifically, our results indicate that a 1 $\mu g/m^3$ reduction in yearly PM_{10} concentrations leads to a 0.80 percentage point decrease in dementia prevalence for females, while the impact for males is statistically insignificant. The effects are more pronounced for older seniors, with 0.72 and 1.71 percentage points decrease in dementia prevalence for those aged 85–94 and 95+, respectively. Similarly, less educated seniors experience more pronounced effects, with 0.79 and 0.32 percentage point reductions in dementia for those with elementary and secondary education, respectively. Statistically insignificant impacts on those aged less than 85 and those with an education level above high school are observed. Additionally, the effects also vary according to marital status and childhood medical care. We find a more substantial impact on divorced or widowed people (1.47 percentage points) and on people without childhood medical care (1.08 percentage points) than on married people (0.22 percentage points) and on those with childhood medical care (0.58 percentage points). Our subgroup analyses collectively show that specific vulnerable groups, including females, older seniors, individuals with less education, and divorced or

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development of evidence-based strategies and interventions for reducing the risk of dementia. For more details regarding this plan, please refer to https://www.who.int/publications/i/item/global-action-plan-on-the-public-health-response-to-dementia-2017—2025.

[4] The modifiable risk factors identified in Livingston et al. (2020) along with their relative risks and prevalence rates are as follows: less education (relative risk: 1.6, prevalence: 40%), hearing loss (relative risk: 1.9, prevalence: 31.7%), hypertension (relative risk: 1.6, prevalence: 8.9%), alcohol consumption (relative risk: 1.2, prevalence: 11.8%), obesity (relative risk: 1.6, prevalence: 3.4%), smoking (relative risk: 1.6, prevalence: 27.4%), depression (relative risk: 1.9, prevalence: 13.2%), social isolation (relative risk: 1.6, prevalence: 17.7%), physical inactivity (relative risk: 1.4, prevalence: 11%), diabetes (relative risk: 1.5, prevalence: 6.4%), and air pollution (relative risk: 1.1, prevalence: 75%).

[5] Recent epidemiological studies have established an association between air pollution and dementia. Please refer to Peters et al. (2019) for a systematic review.

[6] Several previous studies have explored these quasi-experiments. Rich et al. (2012) compare the biomarker information of young adults before, during, and after the 2008 Olympic Games and find that their health improved during the games. He et al. (2016) also use the same quasi-natural experiment to identify the effects of air pollution on mortality.

widowed seniors, as well as those who lacked childhood medical care, gain more from improvements in air quality. These findings indicate that air pollution's effect on dementia makes its detriments to health substantially larger for these more vulnerable groups. Recognizing these effects can guide public awareness efforts and educational programs, especially in communities where these vulnerable populations are more prevalent.

Our SDID estimator assumes that Beijing and its counterfactual comparison provinces would have experienced similar trends in the absence of the BOG08 regulations. To ensure the validity of the identification, we follow the methodology outlined by Clarke et al. (2023) to examine any differences in pre-BOG08 outcomes between Beijing and the synthetic comparison groups. Our event study results suggest no significant evidence for such differences.

One might be concerned that factors other than air quality improvement might contribute to the decline in dementia prevalence during the period when air pollution regulations were in effect. To address this concern comprehensively, we consider several aspects. First, given the potential influence of income and stock market experience on health conditions (Lindahl, 2005; Engelberg and Parsons, 2016), we examine whether family income is significantly affected by the upsurge in tourism during the BOG08 and consider the potential health implications of stock market fluctuations. Second, we investigate whether there were significant improvements in healthcare infrastructure and resources, including healthcare expenditure, and the number of hospitals, sickbeds, doctors, and nurses. Third, we explore whether other potentially modifiable risk factors for dementia, including smoking, drinking, exercise, hypertension, and diabetes, underwent significant changes. Finally, for comparison, we perform additional placebo tests to evaluate the effect of the BOG08 on nonair pollution-related health conditions, such as cataracts, prostate tumors, bedsores, and arthritis, and air pollution-related conditions, such as asthma. These tests serve to further rule out broader health-enhancing factors. Our results suggest that neither family income, healthcare infrastructure, and resources, common modifiable risks for dementia, nor nonair pollution-related health conditions underwent significant changes during this period. These pieces of evidence increase our confidence that the decrease in dementia prevalence is more likely attributable to the BOG08 air pollution regulations than to other factors.

Moreover, given the possibility that other pollutants such as ozone (O_3), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) may also have decreased during the BOG08 air pollution regulations period, we explore the isolated role of PM_{10} in reducing dementia prevalence by following the approach of Deryugina et al. (2019). The results indicate that the estimated effects remain significant and stable, suggesting that the health improvements observed are primarily attributable to reductions in PM_{10}.

We implement a comprehensive battery of robustness tests and demonstrate that our baseline results and heterogeneous effects are robust to changes in the set of control variables, the composition of the control group, the time periods, or the measure for dementia prevalence used in the SDID estimation. The estimates obtained by applying standard DID and fixed effect instrumental variable estimation also confirm these results. These comprehensive tests confirm that the relationship between PM_{10} concentrations and dementia prevalence is robust and significant, and not merely an artifact of methodology or coincidence.

We also conduct a back-of-the-envelope calculation to quantify the cost savings from reducing dementia cases through improving air quality. Using per-person cost estimates for dementia from the 2010 World Alzheimer Report, we calculate the monetary benefits of reducing dementia cases. Our analysis indicates that in East Asia, the monetary benefit of improving air quality, based on region-specific dementia costs, is estimated to be between 0.97 billion and 2.36 billion US dollars. Moreover, when considering the widest range of global cost estimates, the potential monetary benefits could range from 0.21 billion to as much as 28.10 billion US dollars. These figures highlight not only the health benefits of improving air quality but also its significant economic advantages.

Our study contributes to the following three strands of literature. First, this paper makes a notable contribution to the literature on the relationship between air pollution and dementia. Most existing studies find that higher exposure to air pollution is associated with an increased risk of dementia (as evident in a systematic review by Peters et al. (2019)). However, these correlations do not inherently imply causation. Our paper is among the first few studies to meticulously examine the causal effect of air pollution on dementia.

To our knowledge, only one paper in this strand of literature, namely, Bishop et al. (2023), closely relates to ours. Nevertheless, our paper exhibits major qualitative distinctions from the aforementioned literature. Bishop et al. (2023) provide the first attempt to estimate the causal effect of air pollution on dementia. Their focus is on the role of $PM_{2.5}$ in causing dementia. In contrast, we concentrate on PM_{10}, which is larger in size than $PM_{2.5}$ but still poses significant health risks, especially concerning respiratory and cognitive health. Our attention to PM_{10} aligns with Peters et al. (2019)'s call for more evidence across a broader range of pollutants, thereby enhancing the understanding of the diverse impacts of different air pollutants on dementia. Additionally, unlike (Bishop et al., 2023)'s long-term analysis, we investigate the shorter-term impacts of PM_{10}. By examining the immediate or short-term effects of PM_{10} exposure, our findings complement the literature by providing a more nuanced understanding of how different durations of exposure to various pollutants can influence the progression of dementia. Moreover, Bishop et al. (2023)'s findings are focused on the U.S., which is a developed country where existing research linking air pollution and dementia is often conducted (Peters et al., 2019). Our findings fill this gap and provide insights into how air pollution affects populations in different economic and developmental contexts.

Second, this paper contributes to the growing body of research focused on preventing or delaying dementia. Currently, there is not enough evidence to support a public health campaign for preventing dementia (Yaffe, 2018). The National Academy of Medicine reports highlight three intervention classes with promising evidence: lowering blood pressure for those with hypertension, increasing physical activity, and engaging in cognitive training (Leshner et al., 2017). In contrast, the Lancet review of evidence considers both observational studies and randomized trials without establishing a specific hierarchy of evidence (Livingston et al., 2020). Notably, most studies in this field have concentrated on assessing the impact of reducing lifestyle and health condition risk factors on dementia. However, research into dementia prevention through the reduction of air pollution remains comparatively limited.[7] This paper fills the research gap and informs policy by providing an estimate indicating that reducing PM_{10} concentrations by 10 $\mu g/m^3$ could have prevented up to 578,246 new cases of dementia in China in 2010, representing 6.29% of the total number of people with dementia that year. This substantial figure underscores the importance of addressing air pollution in the context of public health interventions.

Lastly, this paper broadens our understanding of the adverse effects of air pollution on human health and contributes to the literature on the health and economic benefits of reducing air pollution. The primary goal of pollution abatement is to protect human health, but there is still much debate about the specific health effects of air pollution (Currie et al., 2009). A sizable body of literature has documented that air pollution causes numerous health problems, including respiratory infections, lung cancer, and death (e.g., Lleras-Muney, 2010; Pope et al., 2002; Chay and Greenstone, 2003; Currie and Neidell, 2005; He et al., 2016). This study adds valuable insights by providing strong evidence that air pollution can cause dementia. Our economic analysis, based on a 10 $\mu g/m^3$ reduction in air pollution in China in 2010, indicates potential monetary benefits of up to 2.36 billion US dollars due to a decrease in dementia prevalence. This underscores the critical role of air pollution regulation as a potential tool for governments to reduce the public health burden.

The rest of this paper is organized as follows. Section 2 provides a brief discussion of the scientific background on the link between dementia and air pollution. Section 3 introduces the air pollution regulations implemented during the BOG08. Section 4 presents the data. Section 5 outlines our empirical strategy. Section 6 shows the baseline results. Section 7 provides a comprehensive series of checks to ensure the validity of the identification assumptions and the robustness of the results. Section 8 calculates a range of estimates for the monetary benefit of reducing dementia by improving air quality. Section 9 concludes.

2. Scientific background

2.1. The neuropathology and cerebrovascular mechanisms

A growing number of epidemiological studies have explored the correlation between exposure to particulate matter (PM) and dementia. However, the underlying mechanisms through which PM causes dementia are still poorly understood. In this section, we provide a brief summary of the state of the knowledge on the relationship between dementia and exposure to inhaled ambient PM.

The first question when considering the effect of inhaled PM on dementia is whether PM reaches the brain. First, a fraction of inhaled PM can translocate across epithelial barriers and travel along the olfactory route to reach secondary organs, including the brain (Oberdörster et al., 2009; Kreyling, 2016). In addition, a fraction of the PM that is deposited in the lungs may translocate to the circulatory system through the air–blood barrier. Once in the circulatory system, a subset of this PM can translocate across the blood–brain barrier to the brain parenchyma and central nervous system (Elder and Oberdörster, 2006).

After entering the brain, there are three channels through which PM could cause dementia. First, PM may directly damage neurons (Calderón-Garcidueñas et al., 2008), consequently causing dementia. Second, inhaled PM and the resulting inflammation may cause excessive activation of microglia. Then, the excessively activated microglia can elicit the expression of proinflammatory cytokines, which further activate more microglia. Although microglia are necessary for normal brain functioning, excessive activation can result in neurotoxicity, which leads to the initiation and/or amplification of neuronal damage (Block and Hong, 2005), and ultimately causes dementia. Third, excessively activated microglia can stimulate neurons to produce excessive amounts of β-amyloid protein (Aβ-protein) and tau protein. Excess Aβ-protein forms extracellular deposits that stimulate further microglial activation. The excess tau protein is partially released but is also phosphorylated, forming intracellular neurofibrillary deposits. The end result is a positive feedback mechanism that drives the development of dementia (Lee et al., 2015). Fig. 1 summarizes the plausible underlying mechanisms for clarity.

2.2. Short-term air pollution exposure, cognition, and dementia

The interest in air pollution and dementia research is increasing, yet few studies have investigated the short-term effect of air pollution on dementia. Given the intrinsic link between cognitive decline and dementia and this paper's focus on air pollution's short-term effects, this section summarizes several scholarly investigations on the relationships between short-term air pollution exposure, cognition, and dementia.

2.2.1. Indirect evidence on short-term air pollution and dementia

The diagnostic definition of dementia is the chronic and acquired decline in two or more cognitive abilities due to brain disease or injury, which has been used in clinical practice for decades (Arvanitakis et al., 2019). While not all cases of cognitive decline and impairment progress to dementia, dementia itself is characterized by cognitive decline and impairment. Thus, the evidence suggesting a link between short-term air pollution exposure and cognitive decline may offer indirect insights into the potential short-term effects of air pollution on dementia.

The evidence concerning the association between long-term exposure and cognitive decline is rapidly accumulating in epidemiological research (Schikowski and Altuğ, 2020); however, studies focusing on the short-term effects are scarce. Economics research has

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[7] Kivipelto et al. (2018) provide a review of RCT-based lifestyle interventions for preventing dementia and cognitive decline.

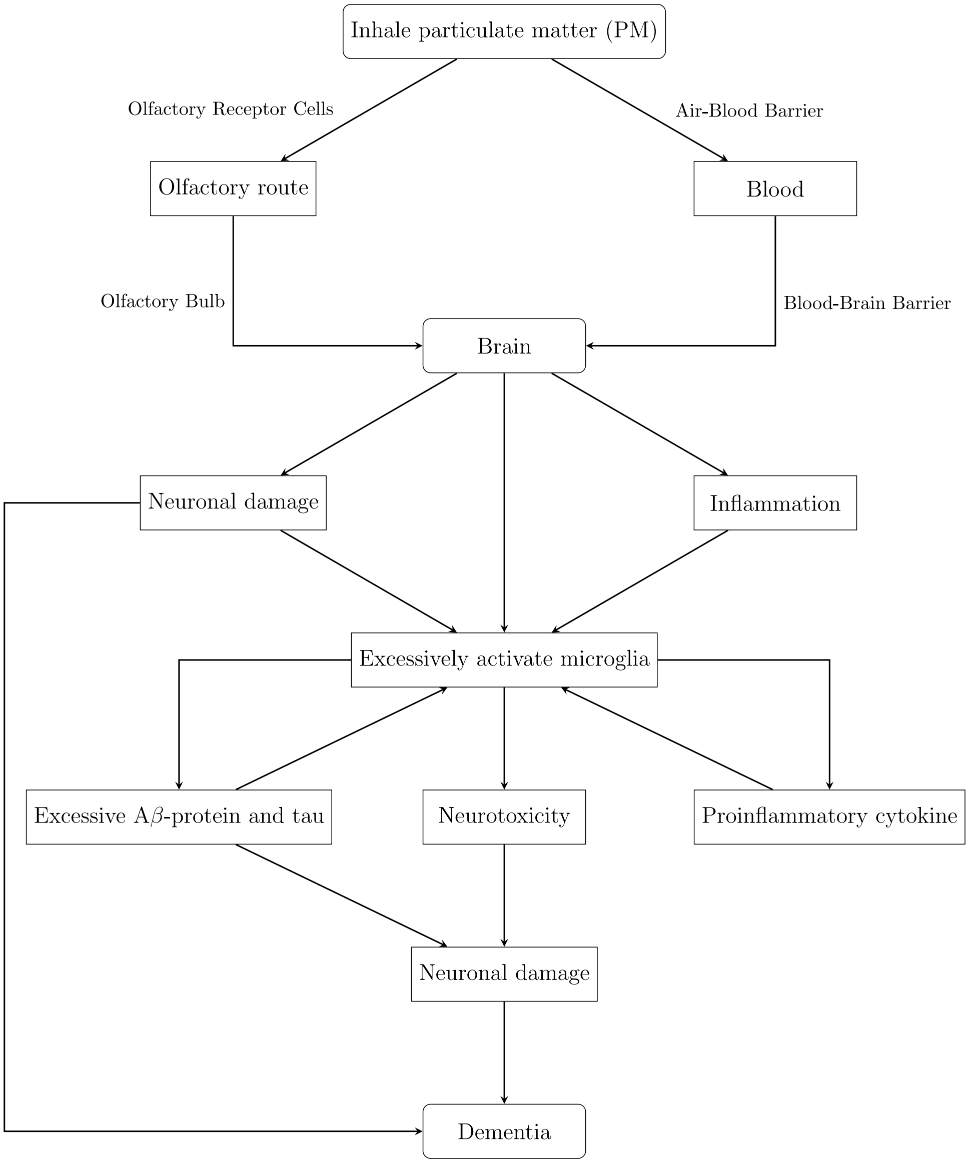

Fig. 1. The mechanisms of how particulate matter cause dementia.

documented a negative relationship between short-term PM exposure and general cognitive tests. Ebenstein et al. (2016) examine the impact of short-term exposure to ambient air pollution on scores on a high-stakes standardized test among Israeli high school students. They find that a one-standard-deviation increase in daily $PM_{2.5}$ exposure is associated with a decline in student performance of 0.93 points, or 3.9 percent of a standard deviation, in the Bagrut score. Zhang et al. (2018) analyze the relationship between air pollution exposure over seven different windows (1 day, 7 days, 30 days, 90 days, 1 year, 2 years, and 3 years) and cognitive performance. They find that except for the effects of 1 day and 7 days of exposure, the impacts of air pollution exposure on cognitive performance are negative and statistically significant. They also conclude that reducing the annual mean concentration of PM_{10} in China would improve people's cognitive performance.

Additionally, recent research in public health shed light on the association between short-term PM exposure and a dementia-related cognitive test, the Mini-Mental State Examination (MMSE). MMSE is a global assessment of an individual's cognitive functioning, including memory, attention, orientation, and language, to indicate overall cognitive ability. It is best known for the clinical diagnosis of dementia (Arevalo-Rodriguez et al., 2021). Shehab and Pope (2019) examine the effect of short-term exposure to particulate matter (PM) air pollution on cognitive performance in their two distinct experimental designs in healthy adults. The results from the MMSE tests show a significant cognitive decline when a cohort experiences a short-term increase after one-hour-long exposure to PM. Gao et al. (2021) elucidate the associations between short-term $PM_{2.5}$ exposure windows (on the same day, 7 days, 14 days, 21 days, and 28 days) and cognitive performance measured by the MMSE in white males with a mean age of 69 years old in the Veterans Affairs Normative Aging Study. Consistent with the experimental findings in Shehab and Pope (2019), they indicate that an increase in short-term $PM_{2.5}$ concentrations is significantly associated with a decrease in the MMSE score.

These studies suggest that the association between short-term PM exposure to air pollution and cognitive decline mirrors findings from long-term exposure. One of the most widely accepted mechanisms of air pollution-induced cognitive decline involves neuroinflammation caused by inhaled airborne particles, which directly enter the brain through nerve connections in the olfactory system (Calderon-Garciduenas et al., 2003, 2004). This process can potentially trigger vascular or endothelial dysfunction and contribute to cognitive impairment (Block et al., 2007; Delfino et al., 2008; Bind et al., 2012; De Silva and Faraci, 2016). These biological studies suggest that cognitive decline induced by air pollution could result from brain injury or damage, potentially leading to the development of dementia.

2.2.2. *Direct evidence on short-term air pollution and dementia*

To date, only one epidemiological study directly provides evidence of the association between short-term air pollution exposure and dementia incidence. Shi et al. (2021) construct two national, U.S. population-based cohorts of elderly individuals aged 65 and above from the Medicare Chronic Conditions Warehouse (2000–2018) and combine these cohorts with high-resolution air pollution datasets to investigate the association between long-term air pollution exposure and the incidence of dementia and Alzheimer's disease (AD). Although the focus is on long-term effects, they find a slightly higher effect estimate of the shorter exposure time windows (within the same year, 1 year, and 5 years) on dementia incidence in the sensitivity analysis. Shi et al. (2021) suggest that shorter-term exposure and dementia incidences, assuming the association is causal (they acknowledge their analysis is not), would imply an acceleration of an existing dementia process (i.e., accelerating cognitive decline that is already well developed) by air pollution. Conversely, longer-term exposure might indicate that air pollution has an effect in more initial stages of neurodegeneration (e.g., being involved in the onset of dementia). Our paper confirms their hypothesis by directly providing the first causal evidence on short-term PM exposure and dementia prevalence.

Besides, a few recent epidemiological studies provide clinical evidence linking short-term air pollution exposure to dementia. Franco et al. (2023) find that an increase in daily exposure to $PM_{2.5}$ is associated with a percentage increase in emergency hospital admissions due to Alzheimer's disease (AD) and Parkinson's disease (PD) in an aged European metropolis. For AD patients, Zhang et al. (2023) observe a positive association between daily air pollutants and their emergency department visits in five U.S. states. Additionally, Liu et al. (2022) show a positive association between short-term exposure (less than 6 days) to ambient air pollution and dementia mortality in Chinese adults. These clinical findings may also suggest that short-term exposure to air pollution could accelerate the dementia process.

3. Air pollution regulations during the BOG08

3.1. *Background*

China's rapid economic growth, industrial development, and urbanization over the past four decades have led to escalating energy consumption, a heavy reliance on coal, and a rapidly expanding vehicular population. Consequently, urban air pollution has emerged as a significant environmental concern. Since the 1980s, numerous Chinese cities have experienced increasingly severe air pollution. Megacities such as Beijing, Shenyang, Xi'an, Shanghai, and Guangzhou consistently ranked among the top 10 most polluted cities in the world during the 1990s (He et al., 2002). Thus, the environmental challenges confronting Beijing became a subject of widespread international discourse and media coverage as early as 1998 when the city submitted its bid to host the 2008 Olympic Games.

On July 13, 2001, the International Olympic Committee (IOC) officially announced Beijing as the host city for the 2008 Olympic Games. The awarding of the games to Beijing prompted heightened scrutiny of the potential ramifications of polluted air on the well-being and performance of athletes participating in the games. Some athletes expressed such profound concern about air quality that they considered wearing masks during competition or abstaining from participating altogether.[8] The IOC Evaluation Committee also acknowledged the environmental challenges facing Beijing, particularly those related to air pollution. Mitigating Beijing's compromised air quality emerged as a paramount concern in the strategic planning efforts of the Beijing Organizing Committee for the Olympic Games (BOCOG) and municipal authorities. Addressing this issue constituted the most salient environmental imperative that both entities had to contend with in preparation for the games.

3.2. *The BOG08 air quality assurance measures*

To ensure optimal air quality in Beijing during the 2008 Olympic Games, the Chinese government implemented a comprehensive set of short-term pollution control measures (UNEP, 2010). Commencing from late 2007 and extending until the conclusion of the

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[8] See the media coverage: "Citing Pollution, Gebrselassie Opts Out of Olympic Marathon", The New York Times, March 2008; and "Olympians air a gripe about Beijing", LA Times, March 2008.

Olympic Games, these regulations constituted perhaps the most extensive efforts in human history to manage air quality over a limited timeframe (Chen et al., 2013).

The first component, known as the pre-Olympic Comprehensive Regulations, was in effect from November 1, 2007, to July 20, 2008. This initiative comprised multifaceted strategies targeting industrial pollution reduction. Measures included a double increase in gas prices, i.e., once in November 2007 and again in June 2008, to discourage automobile usage, the enforcement of more stringent emission standards, and the replacement of high-emission vehicles in the public transit sector. Implemented ahead of schedule on March 1, 2008, the national IV emission standards for motor vehicles led to the removal of 11,000 yellow-label vehicles and the renewal of 2349 environmentally friendly buses and 2941 cabs.[9]

Furthermore, industrial production underwent reductions or suspensions, with power plants mandated to reduce emissions by 30%, even if they had previously met Chinese standards. For instance, Shougang Corporation implemented stringent measures to minimize its production loads and decrease pollutant emissions. Beijing Dongfang Petrochemical Co., Ltd., specifically the Dongfang Chemical Plant, temporarily suspended production. In adherence to the established principles, cement production enterprises, cement grinding stations, concrete mixing plants, and quarrying and lime production enterprises located in the southwest area of the city suspended production. Notably, 18 key metallurgical and building materials enterprises, including Beijing Shougang Hongye Steel Plant and Beijing Flat Glass Group Company, adopted measures such as output reduction, operational adjustments, and enhanced pollution control, achieving a 30% reduction in pollutant emissions while ensuring compliance with emission standards. Similarly, Beijing Yanshan Petrochemical Group suspended the operation of specific facilities, including three distillation units, propane asphalt facilities, and boilers at both the first and second power stations, resulting in a 30% reduction in pollutant emissions while meeting emission standards.[10]

In addition, construction activities were suspended, road cleaning was intensified, and controls were implemented to curtail evaporative emissions. All construction units were mandated to cease earthwork and concrete pouring operations at their respective construction sites. The construction administrative department established a requirement that construction projects lacking the completion of essential tasks, such as earthworks, rock works, foundation pit safety protection, and flood control preparation before July 20, 2008, would not receive approval to commence. Sanitation operation units undertook daily activities, including suctioning and sweeping the city's main roads, secondary roads, important branch roads, and other roads crucial for ensuring seamless services during the Olympic Games.[10] A total of 1462 gas stations, 1387 tank trucks, and 52 oil storage depots within the city's administrative area were either transformed for oil and gas recovery and treatment or suspended if they failed to meet the prescribed discharge standards.[9]

Finally, specific attention was also given to reducing pollution from coal-fired facilities. All coal-fired power plants in Beijing were required to install desulfurization, dust removal, and denitrification facilities. Beijing Jingneng Thermal Power Company, Datang Beijing Gaojing Thermal Power Plant, Huaneng Beijing Thermal Power Company, and Guohua Beijing Thermal Power Branch implemented measures that included the use of low-sulfur high-quality coal and the reinforcement of operation and management practices for pollution control facilities. These efforts aimed to achieve a 30% reduction in pollutant emissions while ensuring compliance with established standards.[9,10]

The Temporary Olympics Regulations, which were effective from July 20, 2008, to September 20, 2008, concentrated primarily on controlling vehicle emissions and promoting the increased use of public transport. Traffic controls played a significant role in decreasing the concentrations of fine particulates, ozone, nitrogen oxide, and other pollutants generated by automotive vehicles in Beijing. Vehicles, including trucks and passenger cars, which failed to meet the Euro I Emissions Standards, faced prohibition from Beijing's roads. Additionally, a comprehensive restriction was imposed on 400,000 yellow-labeled vehicles, barring their presence on Beijing's roads. Nearly half of the 3.4 million registered vehicles were subject to limitations, adhering to the 'odd-even alternative day-off rule.' This rule mandated that vehicles with odd-numbered license plates could only operate on odd-numbered days and conversely, plates ending in an even number could only operate on even-numbered days, with exemptions granted to buses and taxis. Furthermore, during this period, only 30 percent of the total government office vehicle fleet was permitted on the roads. If we consider the inclusion of 400,000 yellow-labeled vehicles, approximately 2 million vehicles daily were not permitted to operate. To fulfill bid commitments, the BOCOG facilitated the provision of low or zero-emission vehicles with minimal noise for transporting Olympic Family members within the Olympic Park and Olympic Villages (UNEP, 2008).

To promote the utilization of public transport during the games, complimentary access to public transport (metro and public buses) for 24 h on the day corresponding to their ticket use was granted to all ticket holders. Additionally, guests and spectators holding Olympic accreditation were provided with unrestricted free access to public transport throughout the games. Notably, the cost of metro and public bus services in Beijing was considerably more economical than those in other cities in China. Specifically, a metro ride in Beijing cost 2 yuan (0.30 US dollars), while the equivalent journey in Shanghai incurred a cost of 5 yuan (0.75 US dollars) or more (UNEP, 2008). These measures were instrumental in reducing reliance on personal vehicles during the Games. According to the committee of the BOG08 and the Ministry of Environmental Protection (MEP) in China (2008), the implementation of these measures resulted in a reduction of more than 60% in total vehicle exhaust emissions (He et al., 2016).

In addition to the aforementioned environmental regulations in Beijing, supplementary measures were introduced to ensure good air quality during the Games in neighboring provinces, including Tianjin, Hebei, Shanxi, Shandong, and Inner Mongolia (UNEP,

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[9] See 2008 Beijing Environment Status Bulletin: https://sthjj.beijing.gov.cn/bjhrb/index/xxgk69/sthjlyzwg/hjjc/507289/index.html.

[10] See more details at "2008 Beijing Notice of Air Quality Assurance Measures in the City during the Olympic and Paralympic Games" issued by the Government of Beijing Municipality: https://www.gov.cn/zwgk/2008-04/14/content_944313.htm.

2008). According to the 29th BOG Air Quality Assurance Measures, which were jointly issued by the Ministry of Environmental Protection and the Beijing Municipal Government in collaboration with the surrounding five provinces, these provinces were mandated to enforce control measures in areas such as dust, motor vehicles, and industrial and coal-fired pollution. For instance, in an effort to mitigate emissions in specific sectors across Beijing's neighboring provinces, factories were obligated to reduce production or undergo temporary shutdowns if they failed to meet national standards by June 2008. Additionally, outdated production facilities in power plants were retired, and desulfurization facilities were instituted.[11]

According to the (UNEP, 2010): "The measures and improvements – many of them permanent – in air quality management implemented by Beijing municipal authorities benefited the population well beyond the games. Several of these permanent measures have become part of national policy in China. They are now also being adopted in other cities in the country".

3.3. The effectiveness of the BOG08 environmental regulations

Many studies have shown that the air pollution control measures implemented in accordance with the BOG08 are effective at reducing air pollution. Using self-conduced particular matter (PM) 10 and 2.5 data collected at Peking University between July 28 and October 7, 2008, Wang et al. (2009) find that on average, PM_{10} and $PM_{2.5}$ concentrations are lower during the Olympic Games than in a non-Olympic period. Cai and Xie (2011) study the effect of the Even-Odd License Plate Law on air pollution during the BOG08 and suggest that this traffic control policy effectively improves air quality in the short term. Schleicher et al. (2012) find that temporary measures during the BOG08, such as shutting down certain industries and reducing traffic, have a very large impact on the reduction of aerosol pollution. Chen et al. (2013) conduct a comprehensive study on the impact of the 2008 Olympic Games on air quality and reveal significant improvements in the air pollution index (API) for Beijing during and after the Games. Viard and Fu (2015) utilize officially published air pollution index (API) data from 2007 to 2009 to investigate the effect of traffic control on air quality and report a decrease in air pollution during traffic restriction days. He et al. (2016) demonstrate that PM_{10} concentrations in Beijing decrease by an average of 18% in 2008 and by 30% during the Games.

4. Data

4.1. Health data

The micro-level health data come from the Chinese Longitudinal Healthy Longevity Survey (CLHLS), the world's most extensive collection of centenarians, along with comparable groups encompassing nonagenarians, octogenarians, and individuals aged 65–79. The CLHLS has conducted face-to-face interviews in 23 of China's 31 provinces and municipalities every 2 to 3 years since 1998. The population in the survey areas constitutes more than 85% of the total population in China.[12] The survey provides information on the health, family, lifestyle, socioeconomic and demographic characteristics of elderly individuals aged 65 or older.[13] To match the air pollution data, we use data from 2000, 2002, 2005, 2008, 2012, and 2014 waves in our analysis.

In our study, we measure dementia status using data from the Mini Mental State Examination (MMSE) provided by the CLHLS.[14] MMSE is the most widely used cognitive test for dementia in U.S. clinical practice (Larson et al., 2016). It is a short and easy-to-administer 30-point questionnaire that covers five major domains of cognitive ability: orientation, registration, calculation, recall, and language. Since a cut-off score of 23 provides a reliable pre-screen diagnosis of dementia (Kochhann et al., 2010), we employ a cut-off score of 23 in our study for the measurement of dementia status. We then obtain the prevalence of dementia at the provincial level by calculating the percentage of individuals with dementia in each province.

According to Song and Wang (2010), 76% of dementia patients in China are not aware of their condition. This underscores the preference for using the MMSE score over diagnostic data to measure dementia, as respondents complete the MMSE regardless of their dementia status. Table 1 presents summary statistics on the key variables, indicating that 31% of our respondents have dementia.[15]

4.2. Air quality data

We obtain daily values for the air pollution index (API) and primary pollutants from 2000 to 2012 from the Chinese Ministry of Environmental Protection (MEP).[16] The MEP has provided daily API values for 86 major cities in China since 2000. The API is a

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[11] See the press conference on "Beijing implements Phase 14 air pollution control measures to improve air quality": https://www.gov.cn/xwfb/2008-02/27/content_903668.htm.

[12] Han Chinese people constitute the overwhelming majority of the population in the surveyed provinces and municipalities, while ethnic minorities make up a very high percentage of the population in the 8 excluded provinces located in the northwestern part of China. This approach is important because Han Chinese individuals can usually provide a reliable date of birth for themselves or close family members, while reported ages among some ethnic minorities are severely biased due to age exaggeration (Coale and Li, 1991).

[13] Initially, the CLHLS project focuses on the oldest-old aged 80 and older. Since 2002 on, those young elders aged 65–79 have also been included.

[14] The CLHLS utilizes a Chinese version of the Mini Mental State Examination (MMSE), which has been tailored to suit China's cultural and socioeconomic conditions. This version is designed to be easily understandable and practically answerable for the oldest-old in the Chinese population (Yi and Vaupel, 2002). Moreover, various adaptations of the Chinese MMSE, all based on the original MMSE framework by Folstein et al. (1975), have been proven reliable and valid for use within the elderly Chinese population, as validated by research such as that by Shyu and Yip (2001).

[15] It is important to understand that the MMSE is primarily a preliminary screening method and not a comprehensive clinical diagnosis. Hence, the identification of dementia in our study should be viewed as an initial assessment, which might differ from in-depth clinical diagnoses. We suggest a cautious approach in interpreting these findings.

[16] The MEP started using a new index, namely, the "air quality index (AQI)", in January 2013. Thus, API data are not available after 2013.

Table 1
Summary statistics for the main variables.

	Mean	Std. Dev	Min	Max
PM_{10} (μg/m^3)	103.11	22.62	52.41	142.00
Dementia prevalence	31%	5.0%	21%	40%
Female	56.4%	3.1%	50.3%	64.1%
Age	86.94	0.96	84.57	88.57
Education (year)	2.32	0.70	1.32	3.97
Wind speed (m/s)	2.15	0.48	1.19	2.99
Temperature (°C)	15.37	4.51	5.32	22.6
Humidity (%)	69.18	13.98	51.69	120.18

Notes and sources: The table includes data on dementia, PM_{10}, wind speed, humidity, and temperature. The unit of observation is a province-year. Dementia data span the years 2000, 2002, 2005, 2008, 2012, and 2014, with corresponding definitions provided in the text. PM_{10}, wind speed, humidity, and temperature data cover the period from 2000 to 2012. Details regarding PM_{10} calculations can be found in Appendix A. Humidity and temperature data are sourced from the China Statistical Yearbooks on the Environment. Wind speed and wind direction data are sourced from the National Meteorological Center of CMA. Wind direction data will be used in the regression analysis, acknowledging that traditional statistical measures such as mean, standard deviation, maximum, and minimum may not be appropriate due to the circular nature of the data.

single number that indicates the air quality on a given day and ranges from 0 to 500. The higher the number is, the worse the air quality on that day. The official Chinese API is determined on the basis of three pollutants: sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and PM_{10}.

The method used by the MEP to construct the API allows us to recover the concentrations of the primary pollutants. From 2000 to 2012, of the 78.8% days when the MEP reported the specific type of pollutant that drove the calculation of the API, 90.89% of the time, the primary pollutant was PM_{10}; 8.88% of the time, it was SO_2; and 0.23% of the time, it was NO_2.[17] Hence, the PM_{10} concentrations can be recovered from the API with a high degree of accuracy. To match the API data to the CLHLS data, we aggregate the population-weighted yearly average PM_{10} to the provincial level.[18] The details on how the PM_{10} concentrations are calculated from the API data are presented in Appendix A.

The reliability of official Chinese air quality data has recently been questioned. Chen et al. (2012) and Ghanem and Zhang (2014) find evidence of underreporting for the API near 100.[19] Nevertheless, Chen et al. (2012) find a significant correlation between the API and two alternative air quality statistics (NASA's Aerosol Optical Depth data and the China Meteorological Administration's visibility data). These correlations do not change significantly when the API is close to 100. They conclude that the reported API does contain useful information on cross-city and temporal variations in air pollution. We also compare the officially reported Chinese API with the remote sensor API data in Figure A1 of Appendix A. The similarity between the two measures reduces our concern regarding the manipulation of the reported API.

We obtain additional data from various sources. Most of the covariates used in our analyses are sourced from the China Statistical Yearbooks, which provide detailed statistics for each province in China. From these yearbooks, we extract information from diverse datasets, including economic indicators (such as gross domestic product (GDP), the share of the secondary industry, and fixed asset investment), weather-related data (including humidity and temperature), and information on health infrastructure and resources (such as healthcare expenditure, and the number of hospitals, sickbeds, doctors, and nurses). For wind speed and wind direction covariates, we use county-level data from Chen et al. (2024), who obtained weather station-level meteorological data for the years 2000–2020 from the China Meteorological Data Service Center. They follow Deryugina et al. (2019)'s method to calculate average wind direction, and then aggregate station-level wind speed and wind direction to county-level by choosing a radius of 200 km and applying the inverse distance weighting (IDW) method (Mendelsohn et al., 1994; Deschênes and Greenstone, 2011). We average their estimates to construct province-by-year wind speed and wind direction data for our analyses.

5. Empirical strategy

In this section, we detail the empirical strategy used to identify the causal effect of air pollution, measured by PM_{10}, on dementia prevalence. The major empirical challenge in the identification of causal effects is that individuals' exposure to air pollution can be altered in a variety of ways, making it endogenous.[20] To explore the exogenous variation in air pollution, we exploit the BOG08 regulations as a quasi-natural experiment. We use the Synthetic Difference-in-Differences (SDID) method proposed by Arkhangelsky et al. (2021) to identify the effect of the BOG08 on both PM_{10} and dementia prevalence. The effect of air pollution on dementia prevalence can then be calculated from these two estimates.

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[17] The MEP does not report the primary pollutant when the API is less than 50.

[18] To protect the privacy of the survey respondents, respondents' locations are available only at the provincial level.

[19] Such manipulation is motivated by the "Blue Sky Award". A blue sky day is defined as a day with an API below 100. A city with at least 80% of the days in a calendar year classified as blue sky days qualifies for the "National Environmental Protection Model City" award.

[20] For a detailed discussion of the endogeneity of air pollution, please refer to Zivin and Neidell (2013).

5.1. Identification challenges

Our strategy to identify the causal effect of the BOG08 on the outcomes of interest benefits from Beijing's short-term air pollution regulatory policy in 2008 and employs panel data covering the policy change in some periods. The basic idea is to compare PM_{10} and dementia prevalence over time between Beijing, which implemented the regulation policy, and other provinces that did not adopt such a regulation. The key is to estimate what would have been the PM_{10} and dementia prevalence in Beijing, had Beijing not implemented a comprehensive set of air quality assurance measures in 2008. To do so, the analysis should be based on reliable counterfactuals for Beijing's PM_{10} and dementia prevalence, which are built on information derived from unregulated provinces in the control group.

In our setting, the Synthetic Control (SC) method, pioneered by Abadie and coauthors (Abadie and Gardeazabal, 2003; Abadie et al., 2010, 2015), and the Difference-in-Differences (DID) method, synthesized by Roth et al. (2023), seem to be two straightforward approaches to implementing the estimation. Nevertheless, neither the SC nor the DID method can alleviate the concerns about the central assumption for identifying the causal effect of the BOG08 on PM_{10} and dementia prevalence; that is, there would be no systematic differences between the outcomes of Beijing and those of a comparison group in the absence of air pollution regulations, conditional on the set of covariates.

Although our single-unit treatment and its introduction at a given time may align well with the empirical setting of the original SC method, there is one major concern in constructing a reliable comparison group for Beijing. The SC method omits the unit fixed effects, which captures the important systematic differences in the levels of outcomes between Beijing and the comparison group. This feature is key in our case. As shown in Panel (a) of Fig. 2, Beijing has, on average, a higher level of PM_{10} than other provinces. Moreover, the provinces may also differ in other characteristics that may drive spreads (e.g., regional policies and the resident's lifestyle) and are not always observable and measurable.

Implementing a standard DID model to construct an accurate comparison group for Beijing may also be problematic. On the one hand, the standard DID method is applied when there is a considerable number of treatment units and when there is a willingness to believe in "parallel trend assumptions". In our scenario, however, we only have a single treated unit, namely, Beijing. In addition, the parallel trend in the raw data may not be plausible, as illustrated in Panel (b) of Fig. 2.[21] On the other hand, the DID method relies on the simple average of the control units and treats each unit in the control group equally. Intuitively, assigning equal weight to Sichuan province, which differs significantly from Beijing in terms of economic and social development, and to Shanghai, which closely resembles Beijing, could introduce bias in constructing counterfactuals for Beijing.

To more explicitly address these challenges, we leverage recent methodological advancements in estimating causal effects with panel data. We implement the Synthetic Difference-in-Differences (SDID) estimator proposed by Arkhangelsky et al. (2021), which combines the advantages of both SC and DID methods.

5.2. Synthetic difference-in-differences

Before presenting the SDID estimator, we first define the equation of interest. In our application, we separately consider two outcomes, namely, air pollution and dementia, measured by PM_{10} and dementia prevalence, respectively. For each province j in year t, the outcome Y_{jt} is given by:

$$Y_{jt} = \alpha + \beta Treated_{jt} + \gamma_j + \lambda_t + X'_{jt}\delta + \varepsilon_{jt} \tag{1}$$

where $Treated_{jt}$ is an indicator variable that equals 1 during and after 2008 for Beijing and 0 otherwise.[22] The province fixed effects, γ_j, control for both observed and unobserved time-invariant characteristics of provinces. The year fixed effects, λ_t, control for year-specific shocks that are common to all provinces. The vector X_{jt} is a set of control variables. We include humidity and temperature as control variables when estimating the effect on PM_{10}, as they have been shown to affect air quality in the previous literature (Fischer et al., 2008; Lou et al., 2019; Liu et al., 2020b). When analyzing the effect on dementia prevalence, we further include gender, age, and education, because they have been highlighted as the most important risks for dementia (Livingston et al., 2020). The coefficient of interest is β, which measures the causal effect of the BOG08 on Beijing's air pollution or dementia prevalence.

The SDID estimation is based on Eq. (1) by introducing two sets of weights, province weights $\hat{\omega}_j^{SDID}$ and time period weights $\hat{\tau}_t^{SDID}$, and solves the following optimization problem:

$$\begin{aligned}&\left(\hat{\beta}^{SDID}, \hat{\alpha}, \hat{\gamma}, \hat{\lambda}, \hat{\delta}\right)\\ &= \underset{\beta,\alpha,\gamma,\lambda,\delta}{\operatorname{argmin}} \left\{ \sum_{j=1}^{N} \sum_{t=1}^{T} \left(Y_{jt} - \alpha - \beta Treated_{jt} - \gamma_j - \lambda_t - X'_{jt}\delta \right)^2 \hat{\omega}_j^{SDID} \hat{\tau}_t^{SDID} \right\}\end{aligned} \tag{2}$$

where the province weights $\hat{\omega}_j^{SDID}$ are selected so that Beijing's PM_{10} and dementia prevalence are approximately parallel to the weighted average outcomes for unregulated provinces in the control group before 2008. These province weights play a similar role as the ones used in the SC method.[23] The time weights $\hat{\tau}_t^{SDID}$ are constructed so that the average outcomes of unregulated

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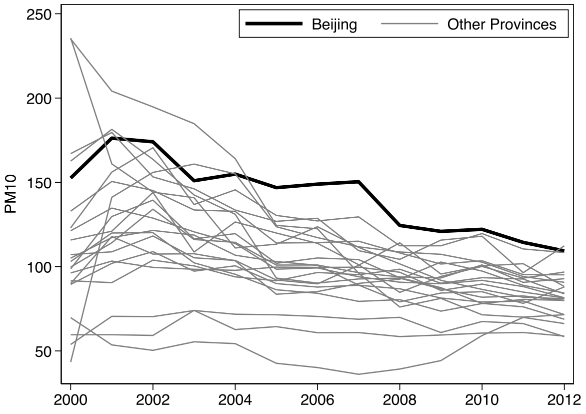
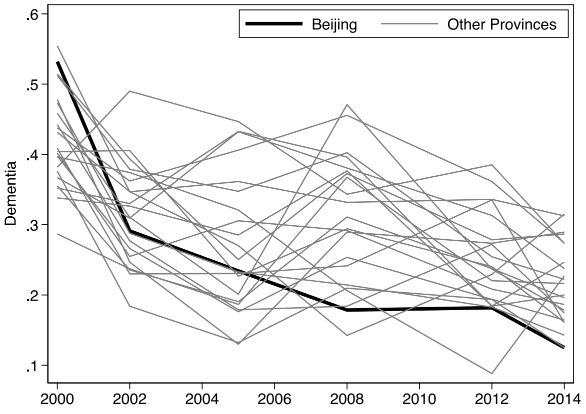
[21] Indeed, as argued in Arkhangelsky et al. (2021) and Abadie et al. (2010), raw data rarely exhibit parallel time trends for treated and control units and thus the common trend assumptions underlying the DID estimator are suspect.

[22] As discussed in Section 3, the drastic air pollution regulations went into effect in November 2007; thus, we include 2008 in the post-treatment period.

[23] As explained in Arkhangelsky et al. (2021), there are two minor differences compared to the weights used in Abadie et al. (2010). First, the SDID unit weights are designed to match pretreatment trends in the outcomes, while SC weights are used to match the pre-treatment levels in the outcomes as closely as possible. Second, the SDID method adds a regularization penalty to the unit weights to increase the dispersion, a feature absent in the SC method.



(a) PM_{10}



(b) Dementia Prevalence

Fig. 2. Air pollution and dementia over time: Beijing vs. Other provinces. *Notes and sources*: Part (a) of the figure presents a comparative analysis of PM_{10} raw data between Beijing and other Chinese provinces, using data spanning from 2000–2012. Part (b) presents a comparative analysis of dementia prevalence raw data between Beijing and other Chinese provinces, using data from years: 2000, 2002, 2005, 2008, 2012, and 2014.

provinces in the control group after the BOG08 differ by a constant from the weighted average outcomes of the same provinces before the BOG08. The time weights balance pre-BOG08 periods with post ones: if a specific pre-BOG08 period is more predictive of post-BOG08 outcomes, then it receives a greater weight.[24]

Drawing inspiration from both the SC and DID methods, the SDID estimator defined in Eq. (2) can alleviate the concerns of identification challenges in Section 5.1. First, similar to SC, it emphasizes the role of unregulated provinces that are on average similar in terms of their past to Beijing and match their pretreatment trends; thus, it relaxes the "parallel trend assumption" for the raw data. Second, like DID, it incorporates both province fixed effects and year fixed effects, enabling the construction of reliable counterfactuals for Beijing even in cases where there are significant differences in the levels of outcomes between Beijing and unregulated provinces. Third, the inclusion of time weights in SDID, which are absent in both SC and DID, can enhance precision by eliminating the role of time periods that greatly differ from the post ones. Finally, the SDID approach enables the construction of

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[24] Arkhangelsky et al. (2021) show that under general regularity conditions, the SDID estimator is consistent and asymptotically normal. We omit the technical details on these weights and conditions for consistency and asymptotic normality and refer readers to this paper for further information.

standard errors for the point estimates of the effects, facilitating systematic inference even in cases where the pretreatment period is short. Thus, we use this method as the main empirical strategy and interpret our results.[25]

To construct a more reliable synthetic comparison for Beijing using the SDID method, the control group in our baseline estimation comprises 5 unregulated provinces in the Eastern region. Based on economic and social development, the National Bureau of Statistics of China categorizes the country into 4 regions: Eastern, Western, Central, and Northeastern regions.[26] The Eastern region (including Beijing) have historically been far more developed than other regions in terms of economic, social, environmental, education, and health factors. It is natural to emphasize provinces that closely resemble Beijing relative to those that do not. The additional penalty in the optimization of the SDID unit weights results in a more dispersed allocation across control units than that of the SC method (Arkhangelsky et al., 2021). This introduces the possibility of assigning weights to provinces in other regions that are very dissimilar to Beijing if included in the control group, potentially leading to a less accurate counterfactual comparison group for Beijing. Additionally, provinces in our sample including Tianjin (Eastern), Hebei (Eastern), Shanxi (Central), Liaoning (Northeastern), and Shandong (Eastern), which are geographically adjacent to Beijing or implement supplementary measures, are also excluded from the baseline analysis because of our concern that they may contaminate estimates. In Section 7.2, we conduct a series of robustness checks using data from all available provinces and find that the effects are closely aligned and remain statistically significant.

For identification, the SDID estimator defined in Eq. (2) assumes that Beijing and the synthetic comparison group constructed by the estimated province weights $\hat{\omega}_j^{SDID}$ and time weights $\hat{\tau}_t^{SDID}$ would have experienced parallel (similar) trends before 2008. We check this common trend assumption in Section 7.1. For standard error calculation, we adopt (Arkhangelsky et al., 2021)'s placebo variance estimator given our single treated unit setting.[27] We perform a set of placebo tests wherein we simulate a scenario where an unregulated province from the control group is treated, even though it is not. The variance of the SDID estimate obtained from these placebo tests serves as the placebo variance for the SDID effect estimate. This placebo variance is then used to construct a confidence interval. As robustness checks, we also employ the standard DID approach to estimate Eq. (1) and implement fixed-effect instrumental variable estimation as outlined in He et al. (2016) to assess the effect of PM_{10} on dementia prevalence in Section 7.2.3. Our findings indicate that all the results remain qualitatively unchanged.

6. Results

We first present our baseline results followed by the heterogeneous effects. For all of our analyses, we present the estimated effects along with the corresponding standard errors.

6.1. The effect of PM_{10} on dementia prevalence

6.1.1. The effect of the BOG08 on PM_{10}

We begin by presenting the results of the BOG08 on air quality. Table 2 presents the estimation results for air pollution based on Eq. (2).

Column 1 provides the results from our baseline model with province and year fixed effects only. The results based on the baseline model indicate that the BOG08 effectively reduced the PM_{10} concentrations in Beijing by 24.187 $\mu g/m^3$. Column 2 through Column 5 then sequentially add four potential weather confounding variables: wind direction, wind speed, humidity, and temperature, to the baseline model to address potential bias. The results based on these four columns indicate that the inclusion of wind direction, wind speed, temperature, and humidity has little impact on the estimated effect, lending further support to our identification strategy. In Column 5, we present our preferred specification in which we include wind direction, wind speed, temperature, humidity, province, and year fixed effects. Overall, the results indicate that the BOG08 has a significantly positive effect on air quality in Beijing, and these results are robust to the inclusion of additional covariates. According to our preferred specification in Column 5, the estimated results suggest that the BOG08 effectively reduces PM_{10} concentrations in Beijing by approximately 26 $\mu g/m^3$. In another study, He et al. (2016) use city-month level data to examine how the air quality regulations affect air pollution during the BOG08. They also find that PM_{10} concentrations decrease by approximately 26 $\mu g/m^3$, which is consistent with our estimated results and provides support for our identification strategy.

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[25] In comparison, the SC estimator omits the province fixed effects γ_j in Eq. (1) and is obtained from the following regression without time weights $\hat{\tau}_t$:

$$\left(\hat{\beta}^{SC}, \hat{\alpha}, \hat{\delta}\right) = \underset{\beta,\alpha,\delta}{\operatorname{argmin}} \left\{ \sum_{j=1}^{N} \sum_{t=1}^{T} \left(Y_{jt} - \alpha - \beta Treated_{jt} - \lambda_t - X'_{jt}\delta \right)^2 \hat{\omega}_j^{SC} \right\};$$

the standard DID estimator solves the same two-way fixed effects regression as in Eq. (1) without both unit weights $\hat{\omega}_j$ and time weights $\hat{\tau}_t$:

$$\left(\hat{\beta}^{DID}, \hat{\alpha}, \hat{\gamma}, \hat{\lambda}, \hat{\delta}\right) = \underset{\beta,\alpha,\gamma,\lambda,\delta}{\operatorname{argmin}} \left\{ \sum_{j=1}^{N} \sum_{t=1}^{T} \left(Y_{jt} - \alpha - \beta Treated_{jt} - \gamma_j - \lambda_t - X'_{jt}\delta \right)^2 \right\}.$$

[26] The eastern region includes Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan*. The central region includes Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan. The western region includes Inner Mongolia*, Guangxi, Chongqing, Sichuan, Guizhou*, Yunnan*, Tibet*, Shaanxi, Gansu*, Qinghai*, Ningxia*, and Xinjiang*. The northeastern region includes Liaoning, Jilin, and Heilongjiang. * indicates that the province was not sampled in CLHLS. For more information about the classification of China's regions, please refer to https://www.stats.gov.cn/zt_18555/zthd/sjtjr/dejtjkfr/tjkp/202302/t20230216_1909741.htm.

[27] Arkhangelsky et al. (2021) argue that both the bootstrap and jackknife-based methods discussed are designed for large panels with many treated units. These methods may be less reliable when the number of treated units is small, and the jackknife is not even defined when there is only one treated unit.

Table 2
The effects of the BOG08 regulations on PM_{10}.

PM_{10}	(1)	(2)	(3)	(4)	(5)
BOG08	−24.187*** (4.923)	−24.752*** (5.237)	−26.650*** (5.805)	−26.620*** (5.766)	−26.461*** (5.779)
Wind direction	N	Y	Y	Y	Y
Wind speed	N	N	Y	Y	Y
Humidity	N	N	N	Y	Y
Temperature	N	N	N	N	Y

Notes and sources: The methodology employed for calculating PM_{10} data is detailed in Appendix A. Wind speed and wind direction data are sourced from the National Meteorological Center of CMA. Humidity and temperature data were sourced from the China Statistical Yearbooks on the Environment. The data spans the period from 2000 to 2012. Control provinces comprise the Eastern 5 provinces: Shanghai, Jiangsu, Zhejiang, Fujian, and Guangdong. Standard errors are presented in parentheses. Significance levels are denoted by asterisks: * signifies significance at the 10 percent level, ** at the 5 percent level, and *** at the 1 percent level.

Table 3
The effects of the BOG08 regulations on dementia prevalence.

Dementia	(1)	(2)	(3)	(4)	(5)
BOG08	−0.188*** (0.028)	−0.215*** (0.054)	−0.205*** (0.053)	−0.210*** (0.055)	−0.217*** (0.044)
Sex	N	Y	Y	Y	Y
Age	N	N	Y	Y	Y
Education	N	N	N	Y	Y
Weather	N	N	N	N	Y

Notes and sources: Weather variables encompass wind direction, wind speed, humidity, and temperature data. Wind direction and wind speed data are sourced from the National Meteorological Center of CMA. Humidity and temperature data are sourced from the China Statistical Yearbooks on the Environment. The dataset covers the years 2000, 2002, 2005, 2008, 2012, and 2014. Control provinces consist of the Eastern 5 provinces: Shanghai, Jiangsu, Zhejiang, Fujian, and Guangdong. Standard errors are enclosed in parentheses, and significance levels are indicated by asterisks: * denotes significance at the 10 percent level, ** at the 5 percent level, and *** at the 1 percent level.

6.1.2. The effect of the BOG08 on dementia prevalence

Table 3 then presents our main results on dementia prevalence based on Eq. (2). Column 1 provides the results of a model that includes province and year fixed effects only. The results based on the baseline model indicate that the BOG08 reduces dementia prevalence by 18.8 percentage points, and the results are significant at the 1% level.

Females account for two-thirds of the entire population of patients with dementia worldwide, and gender is often considered a major risk factor for dementia (Azad et al., 2007). Thus, the effect estimated in Column 1 could be biased by the changes in gender composition. To address this concern, we include a variable for the percentage of females in our regression and present the corresponding results in Column 2. The results in Column 2 are similar to those in Column 1, suggesting that a change in gender composition is not driving our estimated effect.

Age is another important risk factor for dementia (Azad et al., 2007; Mielke, 2018). The probability of suffering from cognitive impairment and dementia increases with age. Thus, it is also possible that the estimated effects are biased by the change in the age composition of survey respondents. To address this concern, we further control for age in Column 3. The estimated results are robust to the inclusion of this covariate, indicating that the change in the age composition of survey respondents is unlikely to bias our results.

A low education level has consistently been associated with an increased risk of developing dementia (Mielke, 2018; Karp et al., 2004). It would bias our estimates if the composition of survey respondents in Beijing consists of an abnormally higher or lower proportion of lower-educated individuals after 2008. Therefore, we further include years of education in our analyses and present the corresponding estimates in Column 4. The results change little after controlling for education, suggesting that the estimated effects are not driven by the increase in lower-educated respondents in Beijing after the BOG08.

Finally, to be consistent with our preferred specification for the analyses on air quality, we also control for wind direction, wind speed, humidity, and temperature in our analyses on dementia and present the results in Column 5. Overall, the inclusion of weather conditions has little impact on the estimated effects. The results based on this specification show that the BOG08 reduces the dementia prevalence among elderly individuals by 21.7 percentage points.

6.1.3. The effect of PM_{10} on dementia prevalence

In this study, we aim to establish a direct link between PM_{10} and dementia. Our findings indicate that the BOG08 results in a reduction of yearly PM_{10} concentrations by 26.461 $\mu g/m^3$, and this change is accompanied by a 21.7 percentage point decrease in dementia prevalence. To understand the impact of PM_{10} on dementia, we divide the decrease in dementia prevalence by the corresponding reduction in PM_{10} levels. This approach reveals that a 1 $\mu g/m^3$ increase in yearly PM_{10} concentration leads to a

Table 4
The effect of 1 μg/m^3 increase in PM$_{10}$ on dementia prevalence.

Dementia	(1)	(2)	(3)	(4)	(5)
1 μg/m^3 PM$_{10}$ effect (% points)	0.71	0.81	0.77	0.79	0.82
Deviation from mean (%)	2.07	2.37	2.26	2.32	2.39
Sex	N	Y	Y	Y	Y
Age	N	N	Y	Y	Y
Education	N	N	N	Y	Y
Weather	N	N	N	N	Y

Notes and sources: Weather variables encompass wind direction, wind speed, humidity, and temperature data. Wind direction and wind speed data are sourced from the National Meteorological Center of CMA. Humidity and temperature data are sourced from the China Statistical Yearbooks on the Environment. The dataset covers the years 2000, 2002, 2005, 2008, 2012, and 2014. Control provinces consist of the Eastern 5 provinces: Shanghai, Jiangsu, Zhejiang, Fujian, and Guangdong. The effects of PM$_{10}$ on dementia, reported in percentage points, are calculated by dividing the effects presented in Table 3 by 26.461. Additionally, we provide the deviation from the mean (34.25%), calculated against the baseline of Beijing's average dementia rate during the pre-treatment period.

0.82 percentage point (2.39% of the mean) increase in dementia prevalence (see Table 4).[28] This finding emphasizes the significant health risks posed by air pollution and the importance of reducing PM$_{10}$ concentrations in the environment.

When comparing our findings to those of Bishop et al. (2023), we observe nuanced differences in the impacts of particulate matter on dementia. Bishop et al. (2023) identify that a 1 μg/m^3 increase in the decadal PM$_{2.5}$ concentration raises the probability of a new dementia diagnosis by an average of 2.15 percentage points. This higher percentage is likely due to their focus on the long-term effect of PM$_{2.5}$ exposure. In contrast, our study examines the shorter-term impact of PM$_{10}$ on dementia and finds a smaller yet significant increase in dementia prevalence (0.82 percentage points) for a similar increase in PM$_{10}$ concentrations.

Another possible reason for the difference in findings between our study and that of Bishop et al. (2023) is the type of particulate matter examined. While our study investigates the effects of PM$_{10}$, Bishop et al. (2023) focus on PM$_{2.5}$. The smaller size of PM$_{2.5}$ particles allows them to penetrate deeper into the lungs and potentially cause more severe health effects, which could explain their more pronounced impact on dementia risk compared to PM$_{10}$. In line with Peters et al. (2019), there is a recognized need for more research into how various air pollutants, like PM$_{2.5}$, PM$_{10}$, CO, NO$_2$, and NO$_x$, affect dementia. The current evidence linking air pollution to dementia is still limited. Our study provides new insights into the impact of PM$_{10}$ on dementia risk, thereby contributing to the growing understanding of how various air pollutants may affect dementia.

6.2. Heterogeneity in the effects

Our main results indicate that a 1 μg/m^3 reduction in yearly PM$_{10}$ concentrations reduces dementia prevalence by 0.82 percentage points (2.39% of the mean). However, these results could mask substantial heterogeneity in the effects. Thus, in this section, we further explore the effect by gender, age, marital status, educational attainment, and access to medical care during childhood. We present this set of results in Table 5. For each subgroup analysis, we first present the effect of the BOG08 on dementia prevalence. To put these estimates into context, we then use results on air pollution (Table 3) to calculate the effect of a 1 μg/m^3 reduction in yearly PM$_{10}$ concentrations on dementia prevalence for this subgroup and compare the magnitude of this effect with the subgroup's mean prevalence.

Females account for two-thirds of the entire population of patients with dementia worldwide, and gender is often considered a major risk factor for dementia (Azad et al., 2007). Thus, there could be systematic differences in how air quality affects cognitive ability across genders. To explore this hypothesis, we investigate the effect of the BOG08 for males and females separately and present the results in Panel A of Table 5. The results of these analyses suggest that improvements in air quality have a large and significant effect for females but have no impact for males. Our estimates show that the BOG08 reduces dementia prevalence by 21.1 percentage points for females. Taken together with the effects of the BOG08 on air pollution in Table 3, our results indicate that a 1 μg/m^3 reduction in air pollution reduces dementia prevalence for females by 0.80 percentage points, a 1.78% reduction from the mean. The estimate for males, however, is quantitatively much smaller and not statistically significant. These results are not surprising, as females seem to be more vulnerable to cognitive impairment.

As mentioned earlier, age is another important risk factor for dementia (Azad et al., 2007; Mielke, 2018). The probability of suffering from cognitive impairment and dementia increases with age. Thus, improvements in air quality may differently impact members of various age groups. To investigate this possibility, we separately examine the effect for individuals with various age groups and show the results in Panel B of Table 5. Panel B presents the results for individuals aged 65–75 years, 75–85 years, 85–95 years, and older than 95 years in our sample. Based on the results of these analyses, we conclude that the effect is mostly driven by individuals older than 85 years. We estimate that 1 μg/m^3 reduction in yearly PM$_{10}$ concentrations decreases dementia prevalence by 0.72 percentage points for elderly individuals aged between 85 and 94 years and 1.71 percentage points for those

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[28] The mean dementia prevalence (34.25%) is calculated based on data from Beijing before 2008.

Table 5
Heterogeneous effects on dementia prevalence.

Panel A: Gender	Male	Female		
BOG08 effects	−0.054	−0.211***		
	(0.050)	(0.016)		
1 $\mu g/m^3$ PM_{10} effects (% points)	0.20	0.80		
Mean (%)	21.05	44.89		
Deviation from mean (%)	0.95	1.78		
Panel B: Age	65–75	75–85	85–95	95+
BOG08 effects	−0.034	−0.059	−0.191**	−0.453***
	(0.033)	(0.042)	(0.079)	(0.103)
1 $\mu g/m^3$ PM_{10} effects (% points)	0.13	0.22	0.72	1.71
Mean (%)	3.76	9.43	36.64	75.98
Deviation from mean (%)	3.46	2.33	1.97	2.25
Panel C: Education	Elementary	Secondary	University	
BOG08 effects	−0.209***	−0.085***	−0.043	
	(0.055)	(0.031)	(0.255)	
1 $\mu g/m^3$ PM_{10} effects (% points)	0.79	0.32	0.16	
Mean (%)	39.00	15.58	13.85	
Deviation from mean (%)	2.03	2.05	1.16	
Panel D: Marital status	Married	Divorced or widowed		
BOG08 effects	−0.058**	−0.389***		
	(0.029)	(0.065)		
1 $\mu g/m^3$ PM_{10} effects (% points)	0.22	1.47		
Mean (%)	13.49	41.42		
Deviation from mean (%)	1.63	3.55		
Panel E: Childhood medical care	Yes	No		
BOG08 effects	−0.153***	−0.285***		
	(0.035)	(0.107)		
1 $\mu g/m^3$ PM_{10} effects (% points)	0.58	1.08		
Mean (%)	21.32	41.27		
Deviation from mean (%)	2.72	2.62		
Individual characteristics	Y	Y	Y	Y
Weather conditions	Y	Y	Y	Y

Notes and sources: Weather variables encompass wind direction, wind speed, humidity, and temperature data. Wind direction and wind speed data are sourced from the National Meteorological Center of CMA. Humidity and temperature data are sourced from the China Statistical Yearbooks on the Environment. Individual characteristics include sex, age, and education level. Control provinces consist of the Eastern 5 provinces: Shanghai, Jiangsu, Zhejiang, Fujian, and Guangdong. The dataset covers the years 2000, 2002, 2005, 2008, 2012, and 2014. Means are calculated against the baseline of Beijing's average dementia rate during the pre-treatment period. Standard errors are enclosed in parentheses. Significance levels are denoted by asterisks: * for the 10 percent level, ** for the 5 percent level, and *** for the 1 percent level.

above 95 years, accounting for 1.97% and 2.25% of the mean, respectively. The results for people aged between 65 and 84 years are never significant and much smaller in magnitude than those for older cohorts. Our estimated results suggest that the effects of the reduction in air pollution are more pronounced for individuals older than 85 years, which is consistent with our prior expectations.

A low education level has consistently been associated with an increased risk of developing dementia (Mielke, 2018; Karp et al., 2004). Therefore, we also separately investigate how the effect of a reduction in air pollution varies for people with different educational backgrounds and present the corresponding results in Panel C of Table 5.[29] We separately examine the effects for respondents with an elementary-level education or less, secondary-level education (middle school or high school education), and more than high school-level education. Estimates from these analyses suggest that the effects are more pronounced for individuals with less education. Based on our estimates, a 1 $\mu g/m^3$ reduction in yearly PM_{10} concentrations decreases dementia prevalence by 0.79 percentage points for elderly people with at most an elementary-level education, a 2.03% reduction from the mean. For those with secondary-level education, a 1 $\mu g/m^3$ reduction in yearly PM_{10} concentrations decreases dementia prevalence by 0.32 percentage points, a 2.05% deviation from the mean. Yet, the estimated effect for those with more than a high school education is much smaller in magnitude and not statistically significant. Thus, we conclude that people with lower education levels experienced significant and large gains from improved air quality, whereas the BOG08 does not seem to have any impact on individuals with more than a high school education in our sample. This finding is again consistent with our prior belief that improved air quality would be more beneficial for more vulnerable groups.

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[29] More than 50% of our respondents reported zero years of education because the average age of our respondents is 87.

We also investigate whether the effects of a reduction in air pollution differ by marital status. Several previous studies have shown that staying married is associated with a lower risk of dementia (Liu et al., 2020a). Thus, we separately explore the extent to which the effect of the BOG08 varies by marital status and present the results in Panel D of Table 5. Results based on these analyses suggest that a 1 μg/m^3 reduction in yearly PM$_{10}$ concentrations decreases dementia prevalence by 0.22 percentage points for those who are married and by 1.47 percentage points for those who are divorced or widowed, accounting for 1.63% and 3.55% reductions from the mean, respectively. These estimates suggest that air pollution reduction has a larger impact on individuals who are divorced or widowed, suggesting that improvements in air quality benefit those more at risk of developing dementia.

Finally, we separately investigate the effect of air pollution according to whether the respondent had access to medical care during their childhood. Panel E of Table 5 presents our results. This set of estimates suggests that a 1 μg/m^3 reduction in yearly PM$_{10}$ concentrations decreases dementia prevalence by 0.58 percentage points for those who had access to medical care during childhood and by 1.08 percentage points for those who do not, and these effects account for 2.72% and 2.62%, respectively, of the deviation from the mean. These findings suggest that the effects of a decrease in air pollution are greater for those who did not receive medical care during childhood. These results are reasonable because developmental and biological disruptions during the earliest years of life may result in a weakened immune system (Shonkoff et al., 2010; Mistry et al., 2012). Notably, although this finding is not causal,[30] it highlights the potential role of childhood health in health disparities.

Our subgroup analyses indicate that the effects of a reduction in air pollution are more pronounced for females, more elderly individuals, those who were less educated, those who were divorced or widowed, and those without adequate medical care during childhood. The dynamics of the effect heterogeneity shown in Fig. 4 further support the credibility of our findings. These sets of results are highly consistent with the medical literature on at-risk populations, suggesting that improvement in air quality has a greater impact on those who are more vulnerable to developing dementia.

7. Validation tests and robustness checks

7.1. Validation tests

To ensure the robustness and credibility of our identification strategy, we conduct a comprehensive series of tests. Our first set of tests focuses on the trends in PM$_{10}$ levels and dementia prevalence in Beijing compared to those in a control group, examining if they follow a parallel path before the implementation of the BOG08 regulations. This comparison is crucial for establishing a baseline similarity between the regions.

In the second part of our analysis, we explore alternative explanations for the health improvements observed. This includes assessing the impact of the BOG08 regulations on family income, considering the potential effects of increased tourism and stock market fluctuations during the period. Additionally, we examine changes in provincial healthcare infrastructure and resources, such as health expenditures and the availability of medical facilities and personnel. Moreover, we examine modifiable risk factors for dementia, including smoking, drinking, exercise, hypertension, and diabetes. Our objective here is to determine whether the BOG08 has influenced these factors, which could have indirectly affected the development of dementia. Establishing that the BOG08 does not affect these risk factors allows us to link changes in dementia prevalence more confidently to the BOG08's impact on air pollution levels.

We also perform additional placebo tests to investigate the policy's effect on nonair pollution-related health conditions, such as cataracts, prostate tumors, bedsores, and arthritis. This approach is used to determine whether the observed health benefits are specific to air quality improvements or extend to other health areas to rule out broader health-enhancing factors.

Lastly, to strengthen our analysis further, we control for other pollutants such as ozone (O_3), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2). This ensures that the observed effects are specifically attributable to PM$_{10}$ reductions rather than changes in other air pollutants.

7.1.1. Assessing the common trends assumption

In this section, our focus is on assessing the common trends assumption, a critical component for the validation of our study. We adopt the approach detailed by Clarke et al. (2023) in their synthetic analysis framework, which enables us to explore any differences that existed before the treatment between our treated group and the synthetic control groups. This examination is essential to ensure that the trends in both groups were similar before the implementation of the BOG08 regulations, lending credibility to our subsequent findings.

The pre-treatment trend comparison is presented in Fig. 3. Panel A, which focuses on PM$_{10}$ levels, reveals an overall alignment in the pre-treatment trends between the treated and synthetic control groups, except for a notable divergence in 2001. This specific variance is addressed in the robustness test section to confirm that it does not unduly influence our overall estimations.

Similarly, Panel B of Fig. 3 examines the pre-treatment trends in dementia prevalence. The results suggest that there are no significant pre-treatment differences between Beijing and the synthetic control regions. This consistency supports our hypothesis that any post-treatment changes observed in dementia prevalence are likely attributable to the BOG08 regulations.

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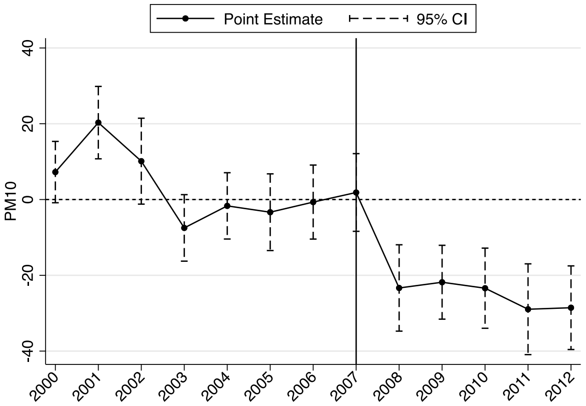
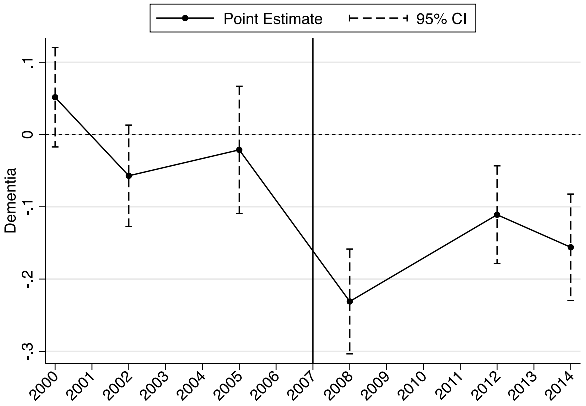
[30] A person who did not receive medical care during childhood is likely to come from a poor family and therefore to have had less nutrient intake or less education.



(a) PM_{10}



(b) Dementia Prevalence

Fig. 3. Dynamic effects of the BOG08 on air pollution and dementia prevalence. *Notes and sources*: Part (a) of the figure presents an event study analysis of the BOG08 regulations' impact on PM_{10} concentrations, with data spanning from 2000 to 2012. Part (b) presents a similar analysis for the regulation's effect on dementia, using data from years: 2000, 2002, 2005, 2008, 2012, and 2014. Both parts include a 95-percent confidence interval, represented by dashed lines.

7.1.2. Ruling out alternative explanations other than air pollution for the findings

In this section, we explore alternative explanations for the observed health improvements following the BOG08.

The first aspect we examine is the impact of the BOG08 on family income. This is particularly relevant given the increased influx of domestic and international visitors to Beijing during this period, which could have influenced local income levels and, consequently, health conditions (Lindahl, 2005).[31] We also consider the broader economic context, including the significant stock market fluctuations between late 2007 and 2008, for potential health implications.[32] Our analysis, as detailed in Table 6, reveals that the impact of the BOG08 on family income in Beijing was both economically and statistically insignificant, indicating no substantial change in family income pre- and post-BOG08. Additionally, Fig. 5 provides a pre-treatment trend comparison, further supporting the validity of the common trend assumption in our study.

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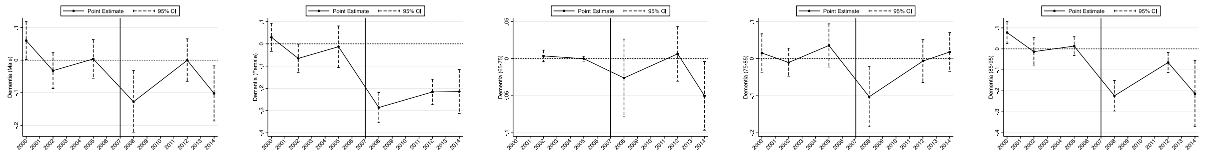
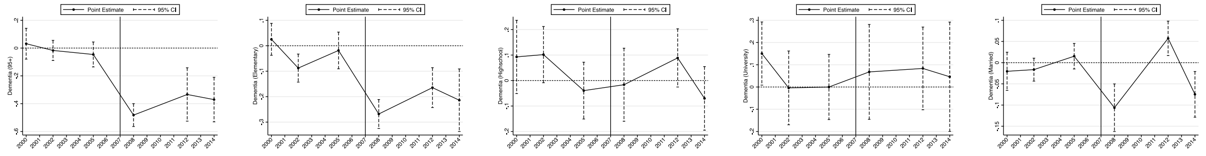
[31] Notably, the health data we employ, which are drawn from the CLHLS, exclusively include individuals aged 65 and above. In China, the official retirement age for men is 60, while for women, it is 50 or 55. Therefore, the primary income source for elderly people is likely retirement pension, which makes it unlikely that their income would significantly benefit from increased visitors during the BOG08. Nevertheless, we consider its potential influence on family income.

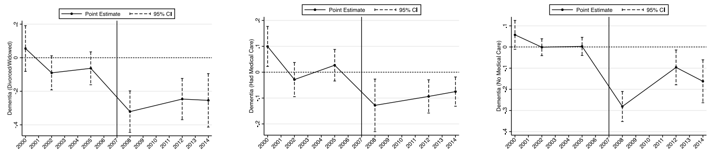
[32] While the Chinese stock market experienced a substantial surge in 2007, the participation rate was extremely low for elderly people. Wu et al. (2010) report a 0% participation rate for seniors with age 65 and older in their 2007 survey. Moreover, the subsequent stock market crash in 2008 should have had a negative impact on health outcomes according to Engelberg and Parsons (2016), implying that the improvement in health outcomes is unlikely due to the significant fluctuation of the stock market during 2007–2008.



(a) Male (b) Female (c) 65-74 (d) 75-84 (e) 85-94



(f) 95+ (g) Elementary (h) Secondary (i) University+ (j) Married



(k) Divorced/Widowed (l) Had Care (m) No Care

Fig. 4. Dynamic heterogeneous effects of the BOG08 on dementia prevalence. *Notes and sources*: This figure provides a comprehensive event study analysis, showcasing the Dynamic Heterogeneity Effects of the BOG08 regulation on dementia, using data from the years 2000, 2002, 2005, 2008, 2012, and 2014. It is divided into sub-figures labeled from (a) to (m), each focusing on different demographic and socioeconomic factors. These include variations by age, gender, education level, marital status, and whether individuals had access to medical care during childhood. Additionally, all sub-figures include a 95-percent confidence interval, represented by dashed lines.

Table 6
Validation test: Impact assessment of the BOG08 on family income.

Family income (yuan)	(1)	(2)	(3)	(4)	(5)
BOG08	2690 (13 200)	8430 (15 700)	6860 (15 000)	7600 (15 100)	7600 (15 100)
Sex	N	Y	Y	Y	Y
Age	N	N	Y	Y	Y
Education	N	N	N	Y	Y
lnrGDP	N	N	N	N	Y

Notes and sources: Family income data are sourced from the CLHLS. The dataset covers the years 2000, 2002, 2005, 2008, 2012, and 2014. Control provinces consist of the Eastern 5 provinces: Shanghai, Jiangsu, Zhejiang, Fujian, and Guangdong. Standard errors are enclosed in parentheses, and significance levels are indicated by asterisks: * denotes significance at the 10 percent level, ** at the 5 percent level, and *** at the 1 percent level.

Second, we examine the impacts of the BOG08 on healthcare infrastructure and resources. In particular, we focus on health expenditures and the availability of medical facilities and personnel, such as hospitals, nurses, sickbeds, and doctors. Understanding whether there were significant changes in these areas post-BOG08 periods is crucial for determining whether the effects of the BOG08 can be isolated from other developments occurring at the same time.

Our findings, which are shown in Table 7, reveal that the BOG08 does not have a significant impact on health expenditure or the number of hospitals, nurses, sickbeds, and doctors. In addition, Fig. 6 provides a comparison of trends before the treatment, which helps support the reliability of our common trend assumption in the study. This comparison ensures that the health improvements we are investigating are more likely due to the BOG08 than to other factors in the healthcare environment.

Lastly, we focus on evaluating the impact of the BOG08 on potentially modifiable risk factors for dementia. Livingston et al. (2020) identifies 12 such factors, including education, hypertension, obesity, hearing loss, traumatic brain injury, alcohol misuse, smoking, depression, physical inactivity, social isolation, diabetes, and air pollution. In addition to education and air pollution, however, due to data limitations, our analysis here concentrates on another five risk factors: smoking, drinking, exercise, hypertension, and diabetes.

Our goal is to determine whether the BOG08 has influenced these factors, as changes in them could indirectly affect the development of dementia. Our findings, showcased in Table 8, indicate that the BOG08 has no significant impact on these modifiable risk factors. This result is pivotal because it suggests that the observed reduction in dementia prevalence is more directly linked to improvements in air quality, rather than alterations in these specific risk factors. This conclusion is reinforced by Fig. 7, which shows consistent pre-treatment trends.

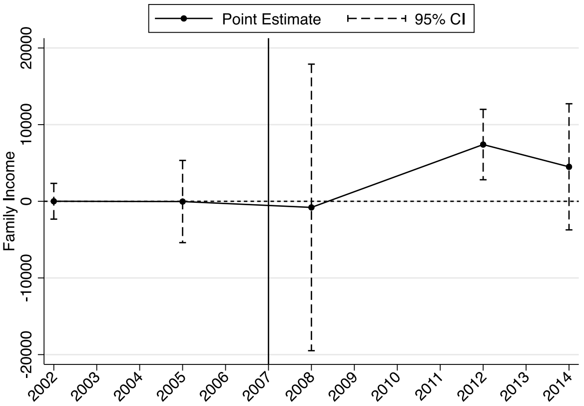
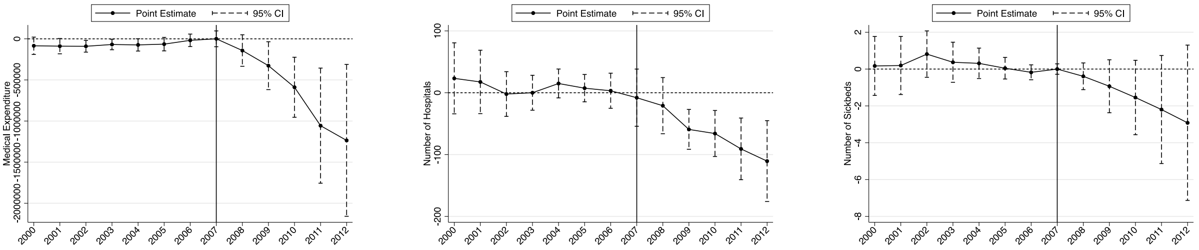


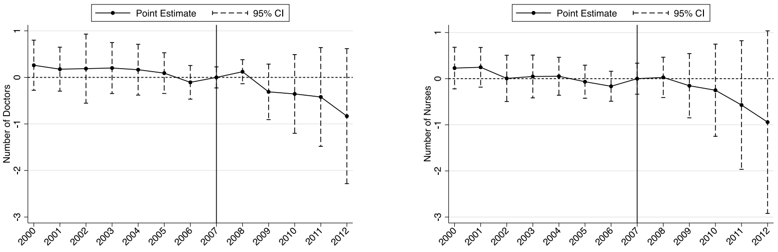
Fig. 5. Dynamic effects of the BOG08 on household income. *Notes and sources*: The figure provides an event study analysis of the BOG08 regulations' impact on family income, using data spanning from the years 2000, 2002, 2005, 2008, 2012, and 2014. The analysis includes a 95-percent confidence interval, represented by dashed lines.



(a) Healthcare Expenditure

(b) Number of Hospitals

(c) Number of Sickbeds



(d) Number of Doctors

(e) Number of Nurses

Fig. 6. Dynamic effects of the BOG08 on health services availability. *Notes and sources*: This figure offers a detailed event study analysis of the dynamic effects of the BOG08 regulations on health service availability, covering the period from 2000 to 2012. It consists of sub-figures (a) to (e), each exploring a different aspect of health services: provincial healthcare expenditure, number of hospitals, number of sickbeds, number of doctors, and number of nurses. Additionally, all sub-figures include a 95-percent confidence interval, represented by dashed lines.

Table 7
Validation test: Impact assessment of the BOG08 on health services Availability.

Health services	Healthcare expenditure	Hospitals	Sickbeds	Doctors	Nurses
BOG08	−670 000	−68.83	−1.57	−0.35	−0.37
	(487 000)	(45.82)	(2.07)	(1.05)	(0.85)
lnrGDP	Y	Y	Y	Y	Y

Notes and sources: Health Services Availability data sourced from the China Statistical Yearbook. The dataset covers the years 2000, 2002, 2005, 2008, 2012, and 2014. Control provinces consist of the Eastern 5 provinces: Shanghai, Jiangsu, Zhejiang, Fujian, and Guangdong. Standard errors are enclosed in parentheses, and significance levels are indicated by asterisks: * denotes significance at the 10 percent level, ** at the 5 percent level, and *** at the 1 percent level.

Table 8
Validation test: Impact assessment of the BOG08 on the modifiable risk factors of dementia.

Risk factors	Smoking	Drinking	Exercise	Hypertension	Diabetes
BOG08	−0.029 (0.027)	0.049 (0.032)	0.086 (0.081)	0.057 (0.073)	0.062 (0.038)
Sex	Y	Y	Y	Y	Y
Age	Y	Y	Y	Y	Y
Education	Y	Y	Y	Y	Y
Weather	Y	Y	Y	Y	Y

Notes and sources: Weather variables encompass wind direction, wind speed, humidity, and temperature data. Wind direction and wind speed data are sourced from the National Meteorological Center of CMA. Humidity and temperature data are sourced from the China Statistical Yearbooks on the Environment. Risk factors data sourced from the CLHLS. The dataset covers the years 2000, 2002, 2005, 2008, 2012, and 2014. Control provinces consist of the Eastern 5 provinces: Shanghai, Jiangsu, Zhejiang, Fujian, and Guangdong. Standard errors are enclosed in parentheses, and significance levels are indicated by asterisks: * denotes significance at the 10 percent level, ** at the 5 percent level, and *** at the 1 percent level.

Table 9
Validation test: Impact assessment of the BOG08 on health conditions typically unrelated to air pollution.

Conditions	Cataract	Prostate tumor	Bedsore	Arthritis	Asthma
BOG08	−0.030 (0.055)	0.015 (0.029)	0.004 (0.011)	0.022 (0.090)	−0.117*** (0.034)
Sex	Y	Y	Y	Y	Y
Age	Y	Y	Y	Y	Y
Education	Y	Y	Y	Y	Y
Weather	Y	Y	Y	Y	Y

Notes and sources: Weather variables encompass wind direction, wind speed, humidity, and temperature data. Wind direction and wind speed data are sourced from the National Meteorological Center of CMA. Humidity and temperature data are sourced from the China Statistical Yearbooks on the Environment. Health condition data sourced from the CLHLS. The dataset covers the years 2000, 2002, 2005, 2008, 2012, and 2014. Control provinces consist of the Eastern 5 provinces: Shanghai, Jiangsu, Zhejiang, Fujian, and Guangdong. The table reports on health conditions typically unrelated to air pollution, such as Cataract, Prostate tumor, Bedsore, and Arthritis. The table also includes Asthma - a condition related to air pollution - for comparative purposes. Standard errors are enclosed in parentheses, and significance levels are indicated by asterisks: * denotes significance at the 10 percent level, ** at the 5 percent level, and *** at the 1 percent level.

7.1.3. Additional placebo tests

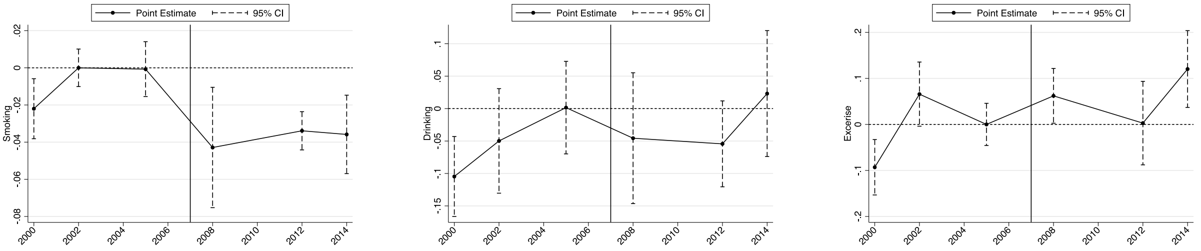
We evaluate the effect of the BOG08 on both nonair pollution-related health conditions, such as cataracts, prostate tumors, bedsores, and arthritis, and air pollution-related conditions like asthma. This approach helps us discern whether the health improvements in Beijing post-BOG08 are confined to air pollution-related conditions or if they extend to other health areas as well. By investigating these varied health conditions, we aim to determine whether the improvements are due to broader health-enhancing factors or are specifically linked to the improvements in air quality.

Table 9 shows that the BOG08 has no significant effects on nonair pollution-related health conditions. Conversely, we observe a notable decrease in asthma cases in Beijing, indicating that the observed health improvements are more closely related to environmental changes than to general improvements in healthcare. This inference is further supported by Fig. 8, which shows consistent pre-treatment trends.

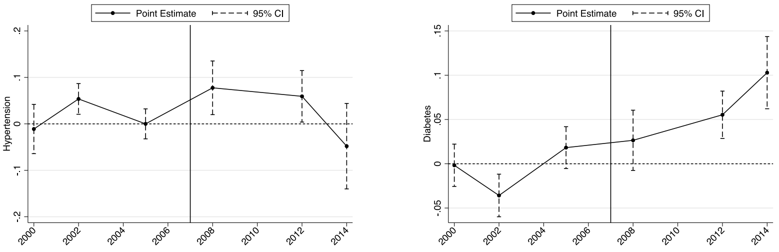
7.1.4. Addressing the influence of co-pollutants on the findings

One potential challenge in interpreting our estimates as the causal effects of PM_{10} is the influence of other air pollutants like ozone (O_3), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2), which can accompany particulate matter. However, SO_2 and NO_2 quickly convert to particulate matter components such as sulfate (SO_4^{2-}) and particulate nitrate, respectively, reducing their independent significance (Luria et al., 2001; Lin and Cheng, 2007; Deryugina et al., 2019). Additionally, epidemiological studies have found no clear association between ozone (O_3) and dementia (Peters et al., 2019; Wilker et al., 2023), which supports our focus on PM_{10} as the primary pollutant of concern.

For further validation, we include controls for other pollutants such as O_3, SO_2, and NO2. This additional analysis ensures that the observed effects are specifically attributable to PM_{10} reductions rather than changes in other air pollutants. However, ground-based monitoring data for O_3, SO_2, and NO_2 before 2013 are not available in China. To address this data gap, we use estimates from Chen et al. (2024), who employed machine learning techniques to generate surface pollutant concentration estimates for periods 2000–2019. This approach combines satellite-based pollution data at a spatial resolution of 45 km × 55 km with recorded

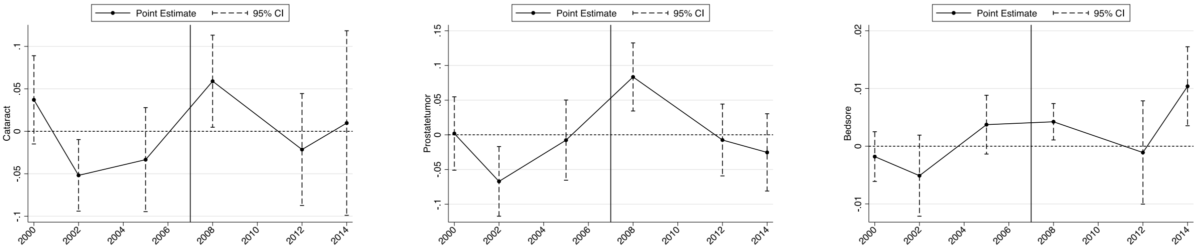


(a) Smoking (b) Drinking (c) Exercise

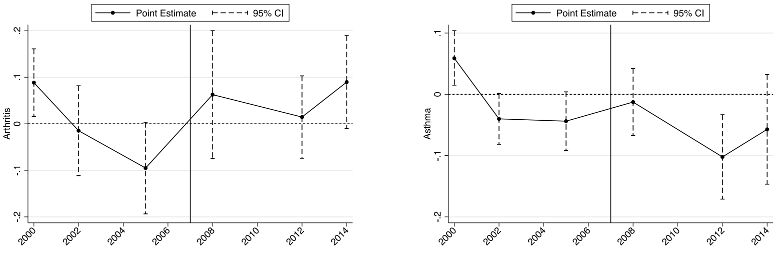


(d) Hypertension (e) Diabetes

Fig. 7. Dynamic effects of the BOG08 on modifiable risk factors for dementia. *Notes and sources*: This figure offers a detailed event study analysis of the dynamic effects of the BOG08 regulations on the modifiable risk factors for dementia, using data spanning from the years 2000, 2002, 2005, 2008, 2012, and 2014. It consists of sub-figures (a) to (e), each exploring different risk factors: smoking, drinking, exercise, hypertension, and diabetes. Additionally, all sub-figures include a 95-percent confidence interval, represented by dashed lines.

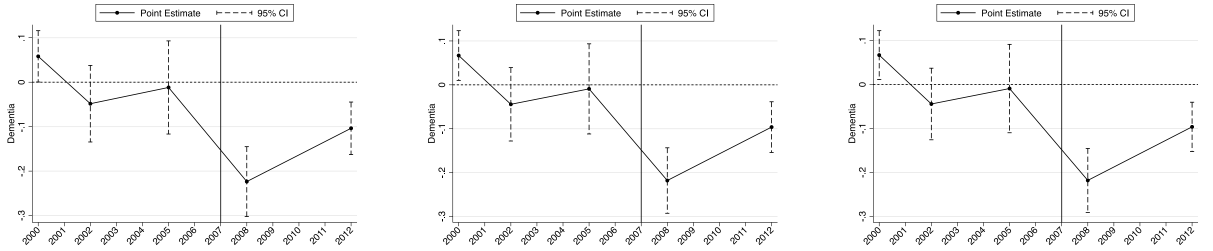


(a) Cataract (b) Prostate Tumor (c) Bedsore



(d) Arthritis (e) Asthma

Fig. 8. Dynamic effects of the BOG08 on health conditions typically unrelated to air pollution. *Notes and sources*: This figure offers a detailed event study analysis of the dynamic effects of the BOG08 regulations on health conditions typically unrelated to air pollution, using data spanning from the years 2000, 2002, 2005, 2008, 2012, and 2014. It consists of sub-figures (a) to (e), each exploring a different health condition: cataract, prostate tumor, bedsore, arthritis, and additionally, asthma, which is typically related to air pollution. This inclusion provides a comparative perspective against conditions not commonly associated with air quality. All sub-figures include a 95-percent confidence interval, represented by dashed lines.



(a) Control O_3 (b) Control O_3 and SO_2 (c) Control O_3, SO_2, and NO_2

Fig. 9. Dynamic effects of the BOG08 on dementia with co-pollutant controls. *Notes and sources*: This figure offers a detailed event study analysis of the dynamic effects of the BOG08 regulations on dementia with co-pollutant controls, using data spanning from the years 2000, 2002, 2005, 2008, and 2012. It consists of sub-figures (a) to (c), which sequentially add O_3, SO_2, and NO_2 as controls. All sub-figures include a 95-percent confidence interval, represented by dashed lines.

Table 10
Robustness analysis: Evaluating the BOG08's effects on dementia prevalence with co-pollutant controls.

Dementia	(1)	(2)	(3)	(4)
BOG08	−0.217*** (0.044)	−0.229*** (0.056)	−0.213*** (0.057)	−0.213*** (0.059)
Baseline controls	Y	Y	Y	Y
O_3	N	Y	Y	Y
SO_2	N	N	Y	Y
NO_2	N	N	N	Y

Notes and sources: Baseline controls include sex, age, education, wind speed, wind direction, humidity, and temperature. Additional control variables data sourced from the China Statistical Yearbook. The dataset covers the years 2000, 2002, 2005, 2008, 2012, and 2014. Control provinces consist of the Eastern 5 provinces: Shanghai, Jiangsu, Zhejiang, Fujian, and Guangdong. Standard errors are enclosed in parentheses, and significance levels are indicated by asterisks: * denotes significance at the 10 percent level, ** at the 5 percent level, and *** at the 1 percent level.

Table 11
Robustness analysis: Evaluating the BOG08's effects on PM_{10} with additional control variables.

PM_{10}	(1)	(2)	(3)	(4)
BOG08	−26.461*** (5.779)	−26.444*** (5.737)	−26.825*** (4.429)	−25.925*** (3.711)
Baseline controls	Y	Y	Y	Y
lnrGDP	N	Y	Y	Y
Share of secondary industry	N	N	Y	Y
Fixed asset investment	N	N	N	Y

Notes and sources: The methodology employed for calculating PM_{10} data is detailed in Appendix A. Baseline controls include wind speed, wind direction, humidity, and temperature. Wind direction and wind speed data are sourced from the National Meteorological Center of CMA. Humidity and temperature data are sourced from the China Statistical Yearbooks on the Environment. Additional control variables data sourced from the China Statistical Yearbook. The dataset covers the years 2000 to 2012. Control provinces consist of the Eastern 5 provinces: Shanghai, Jiangsu, Zhejiang, Fujian, and Guangdong. Standard errors are enclosed in parentheses, and significance levels are indicated by asterisks: * denotes significance at the 10 percent level, ** at the 5 percent level, and *** at the 1 percent level.

surface pollutant concentrations, meteorological, geographical, and socioeconomic factors from the post-2013 period. By assuming that the relationships between these factors remain stable over time, they predicted surface concentrations for earlier periods.

Following Deryugina et al. (2019), we sequentially add the endogenous variables O_3, SO_2, and NO_2 to our main estimating equation. The results, shown in Table 10, indicate that the estimated effects remain significant and stable, suggesting that the health improvements we observe are indeed primarily attributable to reductions in PM_{10}. Fig. 9 shows consistent pre-treatment trends between the treated and synthetic control groups, further supporting the credibility of our findings.

7.2. Robustness checks

In this section, we concentrate on assessing the consistency and stability of our results. This comprehensive assessment includes the introduction of additional control variables, the use of alternative control provinces, the exploration of different time periods, the

Table 12
Robustness analysis: Evaluating the BOG08's effects on PM_{10} with alternative control groups, time period, and model specification.

PM_{10}	(1)	(2)	(3)	(4)	(5)
Panel A: Alternative Control Group 1					
	−24.376*** (9.046)	−23.376*** (8.669)	−23.775*** (8.980)	−23.469** (9.592)	−23.768** (9.442)
Panel B: Alternative Control Group 2					
	−24.741*** (9.337)	−23.514*** (8.771)	−22.626** (8.839)	−22.596** (9.828)	−22.647** (9.774)
Panel C: Alternative time periods (02–12)					
	−24.214*** (4.595)	−24.838*** (4.501)	−24.079*** (5.909)	−24.181*** (5.986)	−24.244*** (5.997)
Panel D: Alternative model specification (standard DID)					
	−30.157** (0.02)	−30.388** (0.02)	−31.173*** (0.002)	−31.033*** (0.002)	−32.132*** (0.002)
Wind direction	N	Y	Y	Y	Y
Wind speed	N	N	Y	Y	Y
Humidity	N	N	N	Y	Y
Temperature	N	N	N	N	Y

Notes and sources: The methodology employed for calculating PM_{10} data is detailed in Appendix A. Wind speed and wind direction data are sourced from the National Meteorological Center of CMA. Humidity and temperature data were sourced from the China Statistical Yearbooks on the Environment. The dataset covers the years 2000 to 2012. For robustness, the analysis includes two alternative control groups and examines an additional time period and model specification. Alternative Control Group 1 comprises Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong, Heilongjiang, Jilin, Henan, Hunan, Hubei, Jiangxi, Anhui, Shaanxi, Sichuan, Chongqing, and Guangxi. Alternative Control Group 2 includes all 23 provinces in the Chinese Longitudinal Healthy Longevity Survey (CLHLS). The alternative time period considered is 2002–2012. The alternative model specification utilized is the standard Difference-in-Differences (DID) approach. For Panel A–C, standard errors are enclosed in parentheses. For the standard DID, following Karaivanov et al. (2021), we report wild bootstrap (cgmwildboot) p-values clustered at the province level in parentheses. Significance levels are denoted by asterisks: * signifies significance at the 10 percent level, ** at the 5 percent level, and *** at the 1 percent level.

consideration of alternative measures of dementia, and the examination of various model specifications. Through these analyses, we aim to illustrate that our conclusions remain both accurate and resilient across a broad spectrum of analytical scenarios, reinforcing the robustness and reliability of our research.

7.2.1. Checking the robustness of the BOG08's effect on PM_{10}

Additional Control Variables As guided by He et al. (2016), we focus on adding three additional control variables: real GDP, the share of the secondary industry, and per capita fixed asset investment. We use real GDP as an indicator of economic growth, reflecting overall economic activity in a region. Its importance comes from its potential link to environmental conditions, especially PM_{10} levels. The share of secondary industry, including manufacturing and construction, is often associated with higher pollution levels. This is due to the nature of these industries, which typically involve processes that produce more pollutants. Finally, we consider per capita fixed asset investment, which helps us understand the extent of infrastructure and industrial development in each province. This is an important factor because it can greatly affect air quality; areas with more investment in these sectors may have different patterns of PM_{10} levels than those with less development.

Table 11 presents the estimated results. The results indicate that the magnitude of the estimates remains consistent after incorporating the additional control variables, implying that our baseline findings are stable across various control variables. Panels (a)–(c) in Figure Appendix C.1 in Appendix C reveal that the pre-trends are closely aligned, though not as precisely as in the baseline scenario.

Alternative Control Groups In our baseline analysis, we focus on the five eastern provinces to construct a synthetic comparison for Beijing. These provinces are selected based on their geographical proximity and developmental similarities to Beijing. To further test the robustness of our results, we explore alternative control groups. First, we expand our control group to include all provinces except those provinces that are geographically adjacent to Beijing or that implement supplementary measures.[33] Second, we consider another control group to include all provinces in the data.[34] This approach allows us to assess whether the inclusion of a broader set of provinces would significantly alter our findings.

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[33] This group comprises Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong, Heilongjiang, Jilin, Henan, Hunan, Hubei, Jiangxi, Anhui, Shaanxi, Sichuan, Chongqing, and Guangxi.

[34] This group includes Tianjin, Hebei, Shanxi, Liaoning, Jilin, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangdong, Guangxi, Chongqing, Sichuan, and Shaanxi.

Panels A and B of Table 12 present the estimated results using these alternative control groups. Notably, although the magnitude of the estimates exhibits a slight decrease, they suggest that our findings remain stable even with varied control groups. However, Panels (d) and (e) in Figure Appendix C.1 in Appendix C illustrate that the pre-trends do not align consistently. This variation in pre-trends emphasizes the suitability of our initial choice of the control group, which includes the five eastern provinces, and suggests that the match in the pre-treatment period is less precise with the alternative groupings.

Alternative Time Periods In this section, we explore the robustness of our baseline results across different time periods. The pre-treatment trend comparison, as presented in Panel (a) of Fig. 3, provides a crucial context for this analysis. These figures reveal a generally consistent alignment in the pre-treatment trends between the treated group (Beijing) and the synthetic control groups. However, there is a notable divergence observed in 2001. This divergence in 2001 raises concerns about its potential impact on the overall results. To address this issue and test the robustness of our findings, we shift our analysis to different time periods, specifically from 2002 to 2012. This adjustment allows us to exclude the year with significant divergence and reassess the BOG08's effect on PM_{10} levels.

The results, displayed in Panel C of Table 12, show that despite the exclusion of a potentially influential year and the change in the time frame, the impact of the BOG08 on PM_{10} levels remains relatively stable and significant. This finding underlines the robustness of our baseline results, suggesting that the conclusions drawn from the original time frame are reliable and consistent. Panel (f) in Figure Appendix C.1 reveals an overall alignment in the pre-treatment trends between the treated and synthetic control groups.

Alternative Model Specifications In this part of our analysis, we shift our focus to an alternative model specification, employing the standard DID method to estimate the effect of the BOG08 on PM_{10}. This approach allows us to validate and compare our findings with those derived from the SDID method used in our baseline analysis.

The results, which are displayed in Panel D of Table 12 and obtained from the standard DID model, are particularly revealing. Each of the outcomes from this model is statistically significant, reinforcing the robustness of our initial findings. Specifically, these results corroborate the significant reduction in PM_{10} levels in Beijing because of the BOG08. This consistency in significance across different model specifications provides a strong foundation for our conclusion that the BOG08 had a notable positive impact on air quality in Beijing.

Furthermore, an intriguing aspect of these results is that the estimated impacts from the standard DID approach are consistently greater than those from the SDID. This difference in magnitude suggests that while both models point toward a significant reduction in PM_{10} levels, the standard DID model estimates a more pronounced effect. This divergence in estimates between the two methods not only demonstrates the robustness of the BOG08 effect across different analytical frameworks but also highlights the potential differences in sensitivity and specificity between the standard and synthetic DID approaches.

Overall, the application of the standard DID model in this alternative specification serves as a valuable cross-validation of our baseline results, affirming the significant impact of the BOG08 on improving air quality in Beijing.

7.2.2. *Checking the robustness of the BOG08's effect on dementia prevalence*

Additional Control Variables Using an approach similar to that used for checking the robustness of the impact of the BOG08 on PM_{10} levels, we now turn our attention to assessing the robustness of the BOG08's effect on dementia prevalence. This involves adding real GDP, the share of secondary industry, and per capita fixed asset investment as additional control variables. These variables provide insights into potential influences on dementia prevalence. Real GDP reflects economic growth and is important here because higher economic activity may be linked to improved healthcare infrastructure and public health policies, which could affect dementia prevalence. The share of secondary industry, encompassing manufacturing and construction, is included because of its possible indirect effects on health through environmental factors. Although its connection to dementia is not as direct as that of PM_{10} levels, understanding the broader health impacts of industrialization is essential. Lastly, per capita fixed asset investment is considered to gauge the extent of infrastructural development, particularly in healthcare.

Table 13 displays the estimated effects, showing consistent estimated magnitudes even after including additional control variables. This consistency suggests that our initial results are robust across different controls. Additionally, Panels (a)–(c) in Figure Appendix C.2 in Appendix C illustrates aligned pre-trends.

Alternative Control Groups We apply the same two alternative control groups previously used in analyzing the robustness of the BOG08's impact on PM_{10} to similarly assess the robustness of the BOG08's effect on dementia prevalence.

Panel A and B of Table 14 present these results. All findings are negative and significant, reinforcing the conclusion that the BOG08 contributes to a reduction in dementia prevalence. However, it is notable that the magnitudes of these effects are smaller than those in our baseline analysis. Additionally, Panels (d) and (e) in Figure Appendix C.2 in Appendix C indicate that the common trend assumptions are not fully met with these alternative groups. These results suggest that the inclusion of these groups may introduce bias into our estimations. They also underscore the suitability of the initial choice of the five eastern provinces as a comparison group for Beijing.

Alternative Measures of Dementia Our primary measure of dementia employs the MMSE test, with literature suggesting a cut-off score of 23 as a reliable indicator of dementia (Kochhann et al., 2010). In this section, we not only reassess the impact of the BOG08 on dementia prevalence using different measurement criteria but also estimate its effect on MMSE scores directly.

Kochhann et al. (2010) propose an adjusted cut-off scale based on educational attainment: dementia is indicated by MMSE scores less than 21 with no education, less than 22 for 1 to 6 years of education, less than 23 for 7 to 12 years, and less than 24 for more than 12 years of education. Utilizing these revised criteria, we reassess the impact of the BOG08 on dementia prevalence.

Table 13

Robustness analysis: Evaluating the BOG08's effects on dementia prevalence with additional control variables.

Dementia	(1)	(2)	(3)	(4)
BOG08	−0.217*** (0.044)	−0.217*** (0.044)	−0.214*** (0.037)	−0.208*** (0.030)
Baseline controls	Y	Y	Y	Y
lnrGDP	N	Y	Y	Y
Share of secondary industry	N	N	Y	Y
Fixed asset investment	N	N	N	Y

Notes and sources: Baseline controls include sex, age, education, wind speed, wind direction, humidity, and temperature. Additional control variables data sourced from the China Statistical Yearbook. The dataset covers the years 2000, 2002, 2005, 2008, 2012, and 2014. Control provinces consist of the Eastern 5 provinces: Shanghai, Jiangsu, Zhejiang, Fujian, and Guangdong. Standard errors are enclosed in parentheses, and significance levels are indicated by asterisks: * denotes significance at the 10 percent level, ** at the 5 percent level, and *** at the 1 percent level.

Table 14

Robustness analysis: Evaluating the BOG08's effects on dementia prevalence with alternative control groups, measures of dementia, and model specifications.

Dementia	(1)	(2)	(3)	(4)	(5)
Panel A: Alternative Control Group 1					
	−0.136*** (0.048)	−0.161*** (0.060)	−0.160** (0.066)	−0.136** (0.065)	−0.134** (0.055)
Panel B: Alternative Control Group 2					
	−0.133** (0.052)	−0.151** (0.059)	−0.154*** (0.059)	−0.140** (0.059)	−0.140** (0.059)
Panel C: Alternative measures: Dementia (Education-based Cut-off)					
	−0.137*** (0.030)	−0.161*** (0.053)	−0.156*** (0.055)	−0.157*** (0.056)	−0.169*** (0.045)
Panel D: Alternative measures: MMSE					
	2.577*** (0.881)	2.688** (1.119)	2.730* (1.510)	2.705* (1.590)	2.824* (1.443)
Panel E: Alternative model specification (Standard DID)					
	−0.181*** (0.002)	−0.172*** (0.002)	−0.182*** (0.002)	−0.167*** (0.002)	−0.169** (0.042)
Sex	N	Y	Y	Y	Y
Age	N	N	Y	Y	Y
Education	N	N	N	Y	Y
Weather	N	N	N	N	Y

Notes and sources: Weather variables encompass wind direction, wind speed, humidity, and temperature data. Wind direction and wind speed data are sourced from the National Meteorological Center of CMA. Humidity and temperature data are sourced from the China Statistical Yearbooks on the Environment. The dataset covers the years 2000, 2002, 2005, 2008, 2012, and 2014. Alternative Control Group 1 comprises: Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong, Heilongjiang, Jilin, Henan, Hunan, Hubei, Jiangxi, Anhui, Shannxi, Sichuan, Chongqing, and Guangxi. Alternative Control Group 2 comprises all 23 provinces in CLHLS. Alternative measures are: (1) using different cut-offs for different education levels, and (2) directly using the Mini-Mental State Examination (MMSE) score. The alternative model specification utilized is the standard Difference-in-Differences (DID) approach. For Panel A–D, standard errors are enclosed in parentheses. For the standard DID, following Karaivanov et al. (2021), we report wild bootstrap (cgmwildboot) p-values clustered at the province level in parentheses. Significance levels are denoted by asterisks: * signifies significance at the 10 percent level, ** at the 5 percent level, and *** at the 1 percent level.

Panels C and D of Table 14 present these findings, confirming that the BOG08 continues to significantly reduce dementia prevalence under the new measurement criteria. Additionally, the BOG08 significantly increases MMSE scores, aligning with expectations. Furthermore, Panels (f) and (g) in Figure Appendix C.2 in Appendix C confirm that the common trend assumptions are met with this alternative measurement approach, supporting the robustness of our findings under different dementia measurements.

Alternative Model Specification We now turn to an alternative model specification by employing the standard DID method. This approach serves as a comparison to the SDID method used in our baseline analysis, allowing us to cross-validate and reinforce our findings.

The results, as shown in Panel E of Table 14, are derived from the standard DID model. All the estimates from this model are significant and negative, which strongly supports the robustness of our initial conclusion that the BOG08 effectively reduces dementia prevalence. While these results align with our earlier findings, it is noteworthy that the magnitude of the impact is modestly smaller

Table 15
Comparing the effects of 1 μg/m^3 increase in PM_{10} on dementia prevalence among alternative empirical methods.

Dementia	(1)	(2)	(3)	(4)	(5)
SDID (% potins)	0.71	0.81	0.77	0.79	0.82
DID (% potins)	0.68	0.65	0.69	0.63	0.66
IV (% potins)	−0.02	−0.01	0.54***	0.55***	0.54***
	(0.0011)	(0.0011)	(0.0015)	(0.0015)	(0.0011)
Sex	N	Y	Y	Y	Y
Age	N	N	Y	Y	Y
Education	N	N	N	Y	Y
Weather	N	N	N	N	Y

Notes and sources: This table estimates the effect of PM_{10} on dementia, calculated by dividing the BOG08's impact on dementia by its effect on PM_{10}. Weather variables encompass wind direction, wind speed, humidity, and temperature data. Wind direction and wind speed data are sourced from the National Meteorological Center of CMA. Humidity and temperature data are sourced from the China Statistical Yearbooks on the Environment. The dataset covers the years 2000, 2002, 2005, 2008, 2012, and 2014. Control provinces: Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong. While these results do not include significance levels, earlier analyses using SDID and DID methods confirm the significance of the BOG08's effects on both PM_{10} and dementia. IV model used for estimating PM_{10}'s effects on dementia, with the BOG08 as the instrumental variable, includes provincial and time fixed effects. Standard errors for IV are in parentheses. Significance levels are indicated by asterisks: * denotes significance at the 10 percent level, ** at the 5 percent level, and *** at the 1 percent level.

Table 16
Benefits of the reduction in dementia prevalence from a 10 μg/m^3 reduction in annual PM_{10}.

	(1) Incidence	(2) Population	(3) Avoided new cases	(4) Benefit (Asia East, USD in Billions)	(5) Benefit (USD in Billions)
Chan et al. (2013)	0.987%	60+	237,804	0.97	0.21–11.56
Li et al. (2007)	1.1%	65+	265,029	1.08	0.24–12.88
Chen et al. (2011)	1.47%	65+	354,176	1.44	0.32–17.21
Prince et al. (2012)	2.4%	65+	578,246	2.36	0.52–28.10

Notes and sources: Incidence is the rate at which new cases occur within a defined population. In 2010, the population of individuals aged 65 or above in China was about 110 million. The number of people with dementia in China in 2010 was estimated to be 9.19 million (Chan et al., 2013). The number of new cases of dementia prevented is calculated as follows: (110 m-9.19m) × Incidence × 0.239. The benefit is calculated as follows: new cases prevented × estimated total cost per person with dementia. The estimated total cost is obtained from the 2010 World Alzheimer Report. In column (4), we use the estimated total cost per person (US$4078) with dementia for East Asia to calculate the benefit. The unit is billions of US dollars. In column (5), we use the lowest total cost per person (South Asia region: 903 US dollars) and the highest total cost per person (North America: 48,605 US dollars) to calculate the benefit.

in the standard DID specification than in the SDID estimation. This difference in magnitude underscores the potential differences in sensitivity and specificity between the standard and synthetic DID methods.

Overall, applying the standard DID model provides a comprehensive and robust validation of our baseline results. These findings affirm that the implementation of the BOG08 has a significant and positive impact on reducing dementia prevalence, demonstrating the effect's consistency across different analytical frameworks.

7.2.3. Comparing the effect of PM_{10} on dementia prevalence with alternative methods

In our study, the primary analysis to assess the effect of PM_{10} on dementia prevalence is conducted using the Synthetic Difference-in-Differences (SDID) method. This approach is complemented by standard Difference-in-Differences (DID) and fixed effect instrumental variable (IV) analyses (He et al., 2016), serving as robustness checks to validate and reinforce the findings from the SDID analysis. Table 15 presents the results from these three different methodologies.

SDID, as the main analytical tool, is pivotal due to its advanced ability to synthesize a control group from multiple comparison units. The SDID method shows a consistent effect size across control variables, with an effect size of 0.82 percentage points when all control variables are included. DID, employed as a robustness check, complements the SDID findings. While it lacks the synthetic control group characteristics of SDID, its simpler approach still yields significant insights. The effect size of 0.66 percentage points aligns closely with the primary findings. This alignment suggests that the primary conclusions drawn from the SDID approach are not artifacts of its complex methodology but are reflective of a genuine relationship between PM_{10} and dementia prevalence. The IV analysis, with its slightly smaller effect size of 0.54 percentage points, offers an additional robustness check of our findings. While this number is lower than those obtained through SDID and DID estimation, it does not negate the overall findings. Instead, it offers a complementary perspective, indicating a consistent causal relationship between PM_{10} and dementia prevalence.

In sum, consistency across methodologies enhances the credibility of our conclusions. Despite their unique analytical framework, each method points toward a similar outcome — that exposure to a higher level of PM_{10} is linked to a greater likelihood of developing dementia. Such agreement across various methods strengthens the argument that the causal relationship between PM_{10} and dementia prevalence is not coincidental or method-dependent but rather robust and significant.

7.2.4. The robustness of heterogeneous effects

In our study, we delve into the heterogeneity in the effects of PM_{10} on dementia prevalence across various demographic factors, including gender, age, education, marital status, and childhood healthcare access. This section is dedicated to evaluating the robustness of these heterogeneous effects. Similar to our baseline estimation, we conduct a thorough set of robustness checks. These include incorporating additional control variables, employing alternative control groups, utilizing different dementia measures, and applying alternative model specifications. The detailed results are presented in Appendix B.

The findings from these robustness checks are consistent and stable. The heterogeneous effects remain stable across a range of additional controls, confirming that the results are not skewed by omitted variables. Similarly, the use of alternative control groups and different measures of dementia do not significantly alter the observed effects, underscoring their validity and suggesting that our conclusions are not contingent on specific group comparisons or dementia definitions. Furthermore, the persistence of these effects across alternative model specifications reinforces their reliability. Overall, these checks substantiate the robustness of the heterogeneous effects of PM_{10} on dementia prevalence, lending further credibility to the study's findings that the influence of PM_{10} is significant, with a greater impact on vulnerable groups.

8. Benefits of reducing dementia prevalence through improving air quality

Among the modifiable risk factors for dementia outlined by Livingston et al. (2020), air pollution stands out for its wide-reaching impact due to its prevalence.[4] While its relative risk of 1.1 seems not as high as that of smoking (relative risk: 1.6, prevalence: 27.4%), hypertension (relative risk: 1.6, prevalence: 8.9%), or physical inactivity (relative risk: 1.4, prevalence: 11%), the fact that 75% of the population is exposed to air pollution significantly increases its importance in public health. This widespread exposure highlights that a vast majority of people are affected by air pollution, amplifying its overall impact on public health. Unlike lifestyle risk factors such as smoking and drinking, which are difficult to influence on a broad scale, air pollution is a modifiable risk factor that can be effectively managed through policy and regulatory measures. Therefore, focusing on air pollution not only tackles a critical dementia risk factor but also aligns with broader public health strategies emphasizing population-level interventions for individual behavioral changes.

According to the World Bank, in 2010, the population of China was 1.33 billion, with 8.25% of the population aged 65 or older. In 2010, the number of dementia cases in China was estimated to be 9.19 million, as reported by Chan et al. (2013). The estimated incidence rates of dementia in China, derived from various studies, are presented in Column 1 of Table 16. If we extend our estimates to the entirety of mainland China, a back-of-the-envelope calculation indicates that reducing yearly PM_{10} concentrations by 10 $\mu g/m^3$ could prevent up to 578,246 new cases of dementia each year.[35]

To determine the monetary benefit, we utilize the per-person cost estimates for dementia from the 2010 World Alzheimer Report. These costs vary regionally, i.e., from 903 US dollars in South Asia to 48,605 US dollars in North America, with the cost in Asia being 4078 US dollars. The monetary value of reducing dementia cases due to improved air quality is calculated by multiplying the total cost per individual with dementia by the number of new cases prevented by a 10 $\mu g/m^3$ reduction in PM_{10}. As shown in Column 4 of Table 16, the estimated monetary benefit for East Asia, using the region-specific dementia cost, ranges between 0.97 billion and 2.36 billion US dollars. Column 5 of Table 16 presents the estimated benefits using the lowest and highest global cost estimates, revealing a range from 0.21 billion to 28.10 billion US dollars in potential benefits.

The calculations presented above illustrate that reducing air pollution can yield substantial benefits through the prevention of new dementia cases. However, it is important to note that these calculations are based on the assumption that the effects of air pollution on health are linear and uniformly applicable across China. Additionally, it remains unclear whether the reduction in dementia cases represents permanent prevention or merely a delay in onset. Even with these considerations, the economic advantage of reducing annual PM_{10} concentrations by 10 $\mu g/m^3$ is significant.

9. Conclusion

Air pollution is acknowledged as a potential modifiable risk factor for dementia. Despite its lower relative risk compared to established lifestyle factors such as smoking, hypertension, or physical inactivity, its remarkably high prevalence rate exceeds that of these other factors. The widespread prevalence of air pollution as a risk factor for dementia, coupled with individuals' limited control over their exposure, underscores the importance of investigating its causal impact. Understanding this causality could pave the way for significant public health interventions and policies aimed at reducing the prevalence of dementia on a broader scale.

We provide quasi-experimental estimates of the impact of air pollution on dementia prevalence, leveraging the stringent air pollution regulations during the 2008 Beijing Olympics and employing a Synthetic Difference-in-Differences (SDID) method. Our results indicate that a 1 $\mu g/m^3$ reduction in annual PM_{10} levels leads to a 0.82 percentage point decrease in dementia prevalence (2.39% of the mean). Further analysis reveals a more pronounced impact on specific vulnerable groups, including females, older

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[35] $578{,}246 = (110m\text{-}9.19m) \times 2.4\% \times 0.239$, where 110 million is the number of people aged 65 or older in China in 2010 and 0.987% is the incidence rate estimated by Chan et al. (2013).

seniors, less educated individuals, divorced or widowed seniors, and those who lacked childhood medical care. These findings underscore the significance of reducing air pollution as a public health strategy against dementia, particularly in protecting these vulnerable subgroups.

Additionally, we highlight the potential benefits of employing air pollution regulations as a population-wide strategy to reduce dementia prevalence. Our economic assessment suggests that reducing annual PM_{10} levels in China by 10 $\mu g/m^3$ in 2010 could have prevented up to 578,246 new cases, resulting in benefits of up to 2.36 billion US dollars. These results emphasize the substantial public health gains attainable through air pollution regulations.

In future research, exploring the nonlinear effects of air pollution on dementia and examining how varying exposure levels impact risk could offer valuable insights. Moreover, elucidating the mechanisms through which air pollution affects the development of dementia may enhance our understanding of its progression, guiding the design of more effective public health interventions.

CRediT authorship contribution statement

Meng Sun: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Naibao Zhao:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Emily Yiying Zheng:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT 3.5 in order to proofread the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Online appendix

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