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Essays on Environmental Economics

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ABSTRACT

ESSAYS ON ENVIRONMENTAL ECONOMICS

By

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Major Department: Economics

This dissertation has two chapters on environmental economics. Chapter one evaluates an energy conservation program in China, the Top-1,000 Energy-Consuming Enterprises Program. The second chapter, co-authored with my colleague Sharad KC, investigates China's location choice of air quality monitors. Both chapters address the principal-agent issue between the central and local governments.

Chapter one empirically evaluates the environmental impact of China's energy conservation program, the Top Thousand Energy-Consuming Enterprises Program. Launched at the beginning of the 11th five-year plan (2006), the program aims at reducing the energy intensity of economic growth by setting annual energy-saving targets on one thousand most energy-intensive companies in nine industries from 2006 to 2010. These companies account for about one-third of China's total energy consumption. In 2011, the government reported an over 95% compliance rate of the energy-saving targets and about 50% overachievement of the national target. However, the environmental impacts of the program are ambiguous. This paper provides a thorough discussion and empirical evidence on whether the firms involved have affected the surrounding surface concentration of air pollutant sulfur dioxide.

Since the program aims at energy savings instead of air quality improvement, the location choice of these companies serves as a random allocation of air quality. I was able to exploit this random aspect of the program by using a quasi-experimental (Difference-in-difference) approach to evaluate the air quality effect of this program. I find this program does not reduce sulfur dioxide emissions in treated establishments, which is consistent with the spatial results. Older governors comply more with energy-saving programs due to concern about political reputation before retirement.

Since 2013, China has added more than four thousand air quality monitoring stations that provide the public with real-time information on six airborne pollutants, i.e., particular matter (P.M.) 2.5, P.M.10, sulfur dioxide (SO2), nitrogen dioxide (NO2), ozone (O3), and carbon monoxide (CO). Authorities manage these monitors at four levels of the government: state, provincial, municipal, and county. Typically, pollution monitors are located where they could be deemed useful, for example, within air polluted areas or near schools, hospitals, road traffic, and industries. While the real-time information has helped individuals, firms and governments make decisions; it is unclear how a government body makes siting decisions. Chapter two aims to answer three questions: Where are the pollution monitors located? What drives the decision to add a new monitor in a particular location? Is there a difference in location choice behavior between central and local governments in China? We find that though central monitors currently locate in cleaner areas than local monitors, the correlation between P.M. 2.5 and monitor location is insignificant. We also find that local governments tend to choose cleaner areas to place monitors, while the effect of air pollution on adding new central monitors is ambiguous.

ESSAYS ON ENVIRONMENTAL ECONOMICS

BY

XIANGYU MENG

A Dissertation Submitted in Partial Fulfillment
of the Requirements for the Degree
of
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ACCEPTANCE

This dissertation was prepared under the direction of the candidate's Dissertation Committee. It has been approved and accepted by all members of that committee, and it has been accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Economics in the Andrew Young School of Policy Studies of Georgia State University.

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DEDICATION

For my parents.

Without your support,

I wouldn't be able to become a Ph.D.

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Table of Contents

List of Tables

List of Figures

Introduction

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Chapter 1 The First to Bear the Brunt: China's Energy Program Evaluation

1.1 Introduction

China is the largest consumer of coal and the highest carbon emission country in the whole world. Back in 2006, at the beginning of the 11th five-year plan, China started to target carbon emission and energy usage. The goal is, by the end of the five-year plan, 2010, China reduces energy usage per growth by 20 percent compared to the 2005 level. Later, in 2009, China promised a more ambitious energy reduction target of 40 to 45 percent by 2020 than the 2005 level. The rapid growth in the past years primarily relied on heavy industries. To deviate itself from massive fossil fuel reliance, China committed to restructuring towards more sustainable economic growth.

Among many policies in the 11th five-year plan, the Top-1,000 Energy-Consuming Enterprises Program accounted for 47% of the total energy saving target for the upcoming five years[1]. The Top-1,000 program is a voluntary agreement program based on initial negotiation and annual auditing. It was launched by the Department of Resource Conservation and Environmental Protection of the National Development and Reform Commission (NDRC), the National Bureau of Statistics (NBS), the State-owned Assets Supervision and Administration Commission, the Office of National Energy Leading Group, and the General Administration of Quality Supervision, Inspection and Quarantine in April 2006 (NDRC, 2006a). The selection of the most energy-intensive 1,000 firms and target setting is conducted by the central government, while local governments, environmental departments, and envi-

[1] China's Sustainable Energy Implementation of the "Eleventh Five-Year Energy Conservation Strategic Plan Research Report No. 5: Thousand Enterprises Energy Conservation Action" and the realization of the 20% energy-saving target in the 11th Five-Year Plan.

ronmental agencies enforce the fulfillment of the targets. Every year in April from 2007 to 2011, the central government provides public reports on the progress of this program, telling the status of energy-saving achievement and whether the firms are still open.

The program has policies that include encouraging the adoption of more energy-efficient equipment and punishing the violation of energy-saving targets. The initial targets will be set lower if the firm has invested or pledged in energy-efficient facilities. If the target is not complied with each year by a firm, both the firm and local government will face penalties, both economically and politically. According to Kostka and Hobbs, 2012, the punishments of not meeting the target include denial of promotion or formal censure for local governors and enterprise managers, "cut water cut electricity," and "regional investment restriction." Politicians in China have limited terms, the stakes are high for compliance on national programs.

The total amount of energy saved regarding this program was around 150 million tons of standard coal equivalent (tce) in the final report of 2011, while the target was set at 100 million tons tce[2]. The total amount of energy consumption for China in 2010 is 3.61 billion tce. Shandong, the largest energy consumption province in China, consumed 363.57 million tce in 2010.[3] In 2011, China planned the reduction target more extensively for the 12th five-year plan. The 12th five-year plan expands the program to around 17,000 firms, the "Top-10,000 Enterprise Energy-saving and Low Carbon Program", by lowing the threshold of their energy consumption from 180 thousand tce to 10 thousand tce, where there are 14,021 industrial firms[4].

[2]Full article can be found at http://www.gov.cn/gzdt/2011-09/30/content_1960586.htm.
[3]The data are from National Statistical Yearbook 2011 and Shandong Statistical Yearbook 2011.
[4]Standard coal equivalents (tces) aren't provided by China's Environmental Statistics Database (CESD).

In 2011, the last report came out saying that 97.7 percent of the firms overachieved the target in the year 2010. Only one firm reported negative energy-saving out of 881 firms in the last report. Despite the promising result of these policies regarding energy saving, the initial energy intensity reduction goal of this voluntary agreement program was not achieved according to Q. Chen et al., 2021. However, due to the strong local enforcement, energy conservation was achieved by reducing and migrating production at the firm level. Besides, there have also been concerns about the reported compliance result because of implicit goals and a lack of audit. According to the original program document in 2006, the initial energy-saving goal was set up both by firms and local government, which was not made public until the 2007 report.

This paper tries to answer whether the top-1,000 program improves local air quality during the 11th five-year plan. There are nine energy-intensive industries in the top-1,000 program, chemical, building materials, non-ferrous metal, coal, electricity, petrochemical, textile, paper, and steel. The program was designed in terms of energy-saving quotas based on province and industry. Each province was assigned a portion of energy-saving target and chose companies in the nine industries that fit the selected criteria.

In all kinds of environmental policies, relative standards on pollution level or energy usage create an incentive for firms to increase production. To complete the standard requirements, firms can either reduce the amount of pollution emission (the enumerator) or increase production (the denominator). Theoretical research and data simulations have shown that intensity control serves as a subsidy on production (Fischer & Springborn, 2011). For this program, Karplus et al., 2020 find that firms with low local economic growth are less likely to comply with the regulation. However, Zhao and Wu, 2016 surveyed ten energy-intensive industrial firms in Jiangsu, China. They found that meeting the standard of emission intensity regulation, both local and nationwide energy-saving programs, is not an incentive for firms to accelerate their production level. The increase in production is more likely to be a reaction to market demand or business expansion. However, Q. Chen et al., 2021 found that the goal of energy conservation became an absolute energy reduction for the treated firms. Therefore, they saw a decrease in production, rather than an increase. But the energy intensity of production did not change.

The impact of the top-1,000 program on air quality can be broken down into two. First, whether there is a relationship between energy conservation and air quality. Studies show that the co-benefit of energy conservation programs in terms of energy saving, environment, and public health improvement exists in many countries (Bell et al., 2008; Zhang et al., 2016). The two kinds of air pollutants, global air pollutants, carbon dioxides, and local air pollutants, share the same source, coal. In terms of China's energy conservation policies, some studies relate air quality to energy conservation programs (Aunan et al., 2004; C. Chen et al., 2007; P. Jiang et al., 2013; Tan et al., 2016). Second, how much of an impact the top-1,000 program has on the local air quality? The papers above approach this issue either using theoretical modeling or state and provincial aggregated data analysis. This paper uses micro-level data, both on air quality and firm performance, and a quasi-experimental method to determine whether there is an impact of the energy-saving program on local air pollution and how much the effect is.

This paper uses satellite data to evaluate the air quality change before and after the program was implemented in 2006. To do that, I, first, use firm-level data to identify the effect of this program on energy consumption, pollution emissions, and production using self-reported data. To verify the treatment effect using external spatial data sources from NASA, I locate the 1,008 companies' 1,175 establishments from the 2006 list of the top-1,000 program. Then, I match the location of the companies with the nearest longitude-latitude datapoint from the NASA sulfur dioxide (SO_2) dataset. Using model (1), I measure the marginal effect of one treated company on the local SO_2 concentration and its growth rate at establishment level. Then, I use model (3) and (4) to find the treatment effect from top 1,000 program on SO_2 at grid level. Furthermore, to understand the political drive of policy compliance, I use local politician data to investigate the heterogeneous compliance with different provincial politicians' age using model (7). I also used event study in find yearly difference between the treated and control establishments and grids.

The remaining of this paper has eight sections. Section 2 is a summary of related literature. Section 3 describes the data. Section 4 is empirical methodology for firm and grid analysis. Section 5 shows the estimated treatment effect of this program on local air pollution, SO_2. Section 6 is the conclusion of this research. Section 7 is a discussion for future research. The last section is the appendix.

1.2 Literature Review

There are some research focuses on the sulfur dioxide emission change in China during the same time. Schreifels et al., 2012 find a significant 14% reduction of sulfur dioxide reduction during 2006-2010. They find that one policy implemented widely in thermal companies is the installation of flue gas desulphurization (FGD) technology. Their research was using aggregate data nationwide. Li et al., 2011 also shows a reduction in sulfur dioxide emission and energy intensity in thermal companies. But the data only covers a few major state-owned thermal companies, and the change of energy intensity varies among these companies.

Regarding energy conservation programs, Aunan et al., 2004 predict a decrease in sulfur dioxide emission and P.M. 10 in Shanxi Province, China. Their research focuses on the coal industry's energy abatement practice. Tan et al., 2016 focus on China's cement industry and find that whether energy conservation programs positively impact pollution reduction depends on technology adoption. These analyses mainly use modeling and simulation using the production and emission parameters of specific industries. Therefore, the empirical effect of energy conservation programs on air pollution in China is unclear.

There has been some research on the top-1,000 program. But it mainly focuses on the financial status and shift of production of the enrolled companies (Q. Chen et al., 2021). This paper fills the literature gap of evaluating the top-1,000 program using micro-level data, especially spatial data, and building the connection between energy conservation programs and local air pollution reduction.

Literature has shown mixed evidence on the political incentives for politicians to comply with energy or environmental programs. Kahn et al., 2015 find the age of provincial politicians has a significant relation to environmental compliance. Younger politicians, especially governors, are more passionate about cleaning up dirty rivers. However, a recent study Wu and Cao, 2021 found no impact of environmental compliance on the provincial governor and party secretary promotions. Evidence also shows that older politicians (mayors) tend to comply more to save their political reputation before retirement (Gang & Kunrong, 2019). This paper will provide more evidence in finding the effect of politician characteristics on implementing energy conservation programs.

1.3 Data Description

1.3.1 Sulfur Dioxide Air Quality Data

The air quality measure in this paper is Sulfur Dioxide (SO_2), specifically Sulfur Dioxide Surface Concentration (kg km-3). Sulfur dioxide has a severe negative impact on human health. According to the United States Environmental Protection Agency[5], short-term exposures to SO_2 can harm the human respiratory system and make breathing difficult. People with asthma, particularly children, are sensitive to these effects of SO_2. High concentrations of SO_2 in the air also lead to other sulfur oxides (SO_x) formation, contributing to particular matter (P.M.) pollution and acid rain. Studying the effectiveness of environmental policies on SO_2 has substantial public health implications. The largest source of SO_2 in the atmosphere is burning fossil fuels by power plants and other industrial facilities. The top-1,000 program focus on reducing energy intensity and usage in large-scale industrial production. Therefore, using the change of local SO_2 concentration as the outcome variable can answer how effective the program is in reducing energy usage in big industrial companies.

[5]https://www.epa.gov/so2-pollution/sulfur-dioxide-basics

Surface concentrations focus on the SO_2 in a near-surface space. It is closer to the area where there are a lot of human activities, therefore, has more impact on public health. The measurement is obtained from NASA's second Modern-Era Retrospective analysis for Research and Applications(MERRA-2) (Gelaro et al., 2017) at $0.625° \times 0.5°$ longitude-latitude grid from 2001 to 2010, which is approximately 70 km × 55 km grid (see Figure 1). There are 3,348 grids each year covering China's landscape[6]. The data from NASA is at a monthly level, while the outcome variable used in this paper is yearly average calculated from the monthly data. Figure 2 shows the mean and 95% confidence interval of the sulfur dioxide surface mass concentration in 2001-2010. The value of sulfur dioxide increases drastically from 2002 to 2008, while leveled off in 2009 and 2010.

Table 1 shows the means and standard errors for treated and control grids from 2001 to 2010. Treated companies locate in more polluted areas on average. The changes of SO_2 over time across the two groups are similar. The spatial analysis of this paper is conducted at $0.625° \times 0.5°$ grid level.

1.3.2 Firm Micro Data

The firm-level energy consumption data is from China's Environmental Statistics Database (CESD) provided by China's Ministry of Environmental Protection. Firm-level financial data is available during this period from the Chinese Industrial Enterprises Database. The geographic location of the power companies is gathered from geocoding the addresses in the Chinese Industrial Enterprises Database using a Chinese map API (Gaode map API). After

[6]The landscape studied in this paper doesn't include Hong Kong, Macao, and Taiwan Province due to lack of economic and political data.

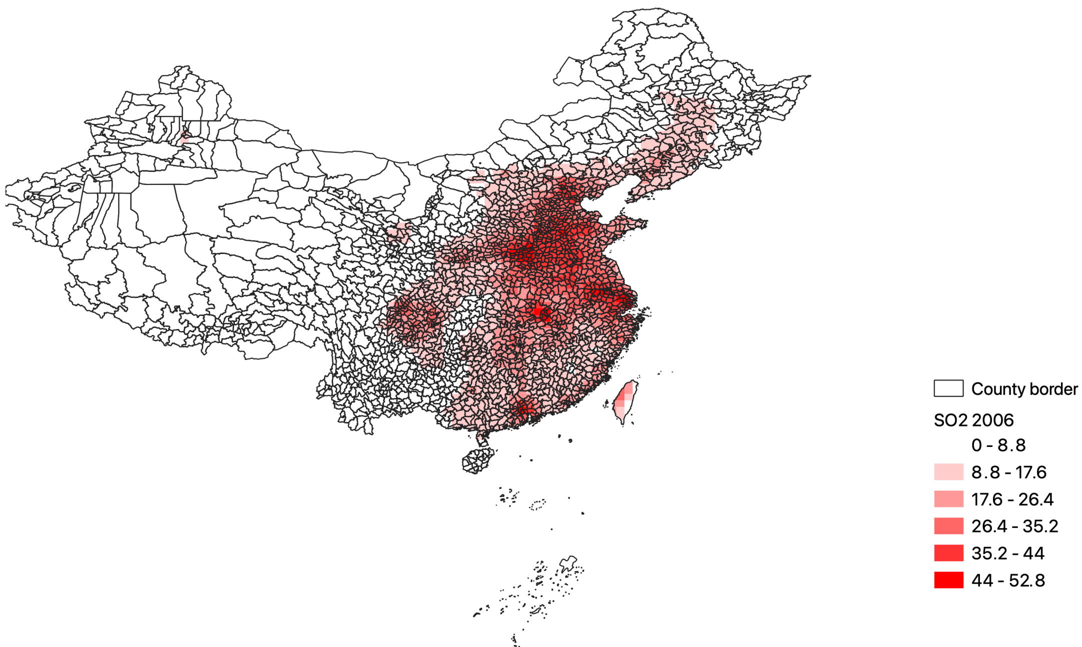

Figure 1 Sulfur Dioxide Surface Mass Concentration (kg km-3) China 2006

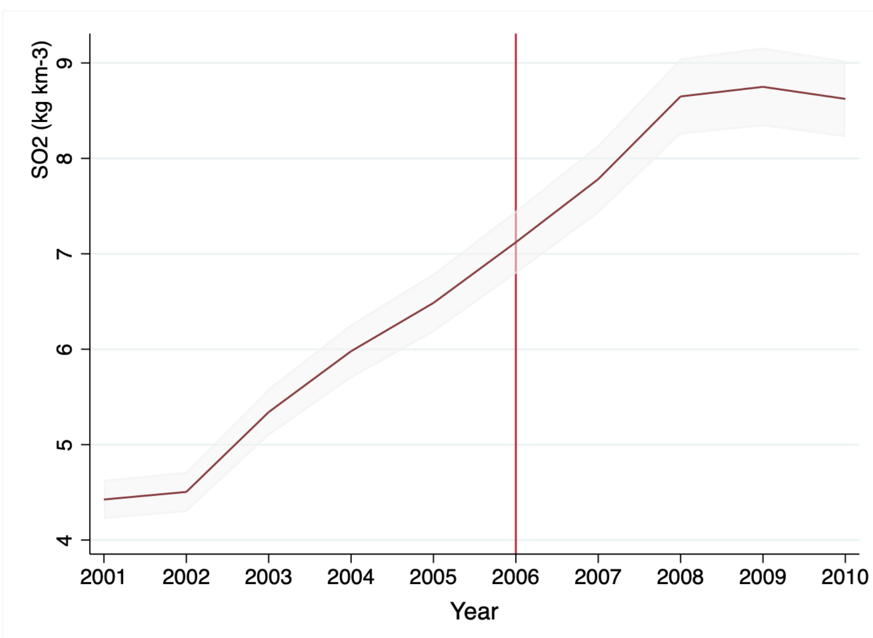

Figure 2 SO_2 Surface Mass Concentration (kg km-3) 2001-2010

Table 1 SO_2 in Treated and Control Grids

	Treated		Control	
	N	Mean (S.D.)	N	Mean (S.D.)
2001	324	13.82 (7.76)	804	11.06 (7.35)
2002	345	14.22 (7.97)	841	11.18 (7.62)
2003	366	16.49 (9.51)	867	12.82 (8.89)
2004	400	18.35 (10.47)	1,065	13.70 (9.78)
2005	394	19.88 (11.27)	1,099	14.70 (10.55)
2006	390	21.80 (12.17)	1,126	15.87 (11.30)
2007	383	23.70 (12.95)	1,160	17.07 (12.11)
2008	346	26.81 (14.53)	1,136	19.19 (13.50)
2009	357	27.58 (15.33)	1,128	19.44 (14.06)
2010	321	26.59 (15.10)	963	19.53 (14.02)

Note: Standard deviations are in the parenthesis after the mean of the variables.

matching the list of firms in the top-1,000 program and top-10,000 program with this firm financial dataset, there are 998 companies from the top-1,000 program used as the treated group, 12,854 companies from the top-10,000 program but not included by top-1,000 program used as the control group. However, since some companies have more than one establishment, there are 1,175 treated and 15,452 control establishments from the two programs that are identified in the finance data. The number of identified establishments differs over the 10-year range. I was able to identify 803 treated and 5,073 control establishments from the CESD dataset.

Table 2 shows summary statistics on all control/treated establishments' finance, energy, and emission status in 2004 because it is the year when the central government uses energy consumption data to determine the initial firm list of top-1,000 programs. In Table 2, SO_2 generation (ton) during industrial production at treated companies are about ten time as high as the control companies. SO_2 reduction (ton) measures the mass of sulfur dioxide reduced by the facilities before emitted to the atmosphere. Treated companies reduced weigh more than the control companies. SO_2 emission (ton) equals toSO_2 generation (ton) minus SO_2 generation (ton). Treated companies emitted higher mass of sulfur but not as much as their generation. Coal (ton) is coal usage in production. Fuel gas desulfurization (FGD) ability (kg hr-1) measures companies' capability to remove sulfur dioxide from flue gases produced from industrial combustion in kilograms per hour. Production (1,000 yuan) means the monetary value of the company's yearly production in one thousand yuans. The control establishments produced about 426 million yuan on average in 2004, while the treated produced over 2 billion yuan. Production share (percent) shows the percentage share of an individual company's production in the industry it belongs to. Treated facilities had higher shares of production in their industry. The numbers of employees were significantly higher at treated companies than control companies. Age (year) is the age of companies, calculated by the current year minus the founded year. The treated companies, in general, had longer histories than the control. The variables in Table 2 are used in firm level analysis in Section 1.4.1.

Table 2 Summary Statistics on Establishments' Financial, Energy and Emission Status in 2004

	Control		Treated	
	N	Mean (S.D.)	N	Mean (S.D.)
SO_2 Generation (ton)	4,414	1,193.63 (5,495.21)	746	10,603.53 (32,633.31)
SO_2 Reduction (ton)	4,414	257.28 (1,781.44)	746	3,998.43 (24,991.23)
SO_2 Emission (ton)	4,414	936.36 (4,978.11)	746	6,605.09 (14,819.70)
Coal (ton)	4,414	89,013.29 (374,389.02)	746	665,258.70 (1,207,295.24)
FGD Ability (kg hr-1)	4,414	321.63 (9,621.09)	746	1,540.42 (16,685.98)
Production (1,000 yuan)	4,440	425,658.50 (1,654,158.13)	749	2,392,393.38 (5,373,976.20)
Production Share (percent)	4,440	0.66 (3.36)	749	0.87 (2.14)
Employee (person)	8,038	999.39 (2,165.70)	1,053	6,234.22 (13,026.21)
Age (year)	7,987	10.93 (14.77)	1,053	19.37 (19.82)

Note: Standard deviations are in the parenthesis after the mean of the variables.

1.3.3 Weather Data

Weather data is gathered from the China Meteorological Forcing Dataset (CMFD), made through a fusion of remote sensing products, reanalysis datasets, and in-situ station data by He et al., 2020. The data dates to 1979 January 1st on a 3-hour and $0.1° \times 0.1°$ resolution. The data used for this paper is yearly average converted to match the grid size of the sulfur dioxide data at $0.625° \times 0.5°$ longitude-latitude level. This dataset includes seven variables: temperature, pressure, specific humidity, wind speed, downward shortwave radiation, downward longwave radiation, and precipitation rate. Details of the variables are listed in Appendix Table A.1.

1.3.4 Economic Controls

The China Statistical Yearbooks (county-level) 2002-2011 and City Statistical Yearbooks 2002-2011 provide annual statistics at county-level divisions from 2001 to 2010. The county-level division is the third-level jurisdiction[7] in China, including autonomous counties, county-level cities, banners, autonomous banners, and city districts. There are about 2,860 county-level divisions in China[8]. The economic controls are converted into grid levels. Grid level economic controls are calculated using a weighted average by population from county economic variables. Figure 3 shows air quality grid and firm locations in 2006 when the program just launched. The areas across multiple counties are labeled by six-digit county codes. The economic factors of grids are calculated by a weighted average of intersected counties. Population density is assumed to be constant within a county in a given year. Thus, the economic

[7]A special case is Hainan province, where county-level divisions are second-level jurisdictions.

[8]The number of county-level divisions decreases from 2,861 in 2001 to 2,856 in 2010.

factors of grids are calculated by the area weighted average of intersections with different counties. For example, the red grid in figure 3 intersects with county 371301, 371322, 371324, 371325, 370401, and 371329. Therefore, economic factors of the red grid are calculated by $\frac{1}{Area_{grid}} \times \sum_i (Area_{grid,c} \times Economic\ Factor_c)$, where c represents six different counties. Table 3 shows grid-level summary statistics for the four economic factors used in this paper. Urban (dummy variable) is generated by whether the population at the grid is greater than the median value of grid population.

1.3.5 Politician Data

The politician data is collected from the Chinese Political Elite Database (CPED)[9] by J. Jiang, 2018 for politician personal characteristics, and https://www.hotelaah.com for terms and locations of office. There are 1,072 provincial politicians in the dataset. The number of politicians for each category is presented in appendix table A.3. Politician data is also geographically converted to grid level. Summary statistics of the politicians at grid area are presented in Table 4 including age, gender, education level, etc..

1.4 Empirical Methodology

The empirical strategy includes two parts:firm analysis and spatial analysis. This paper focuses on finding the marginal treatment effect of a treated firm in the top-1,000 program on sulfur dioxide at the near-surface.

[9]Full data is available at https://www.junyanjiang.com/data.html.

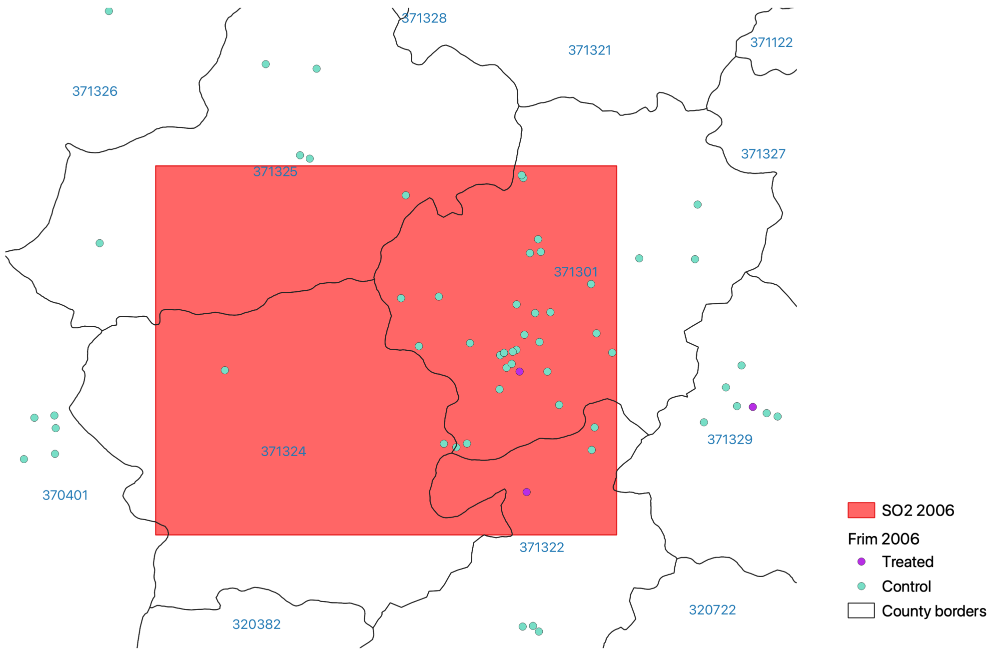

Figure 3 Grid SO_2 and Establishment Locations in 2006

1.4.1 Firm Analysis

The firm analysis contains two steps, kernel propensity score matching, and two-way fixed effect difference-in-difference. In Table 2, treated and control establishments are different in a lot of covariates. The treated top 1,000 companies are expected to be the largest industrial companies, served as industry leaders, and should be different from other companies. Table A.4 in the Appendix shows the covariates are significantly unbalanced before matching. It also shows that after kernel propensity score matching, the covariates are well-balanced.

Equation (1) is the establishment-level analysis specification. This specification is a two-way difference-in-difference design. Outcome variables, $Octcome_{i,t}$, include sulfur dioxide generation, reduction and emission, coal usage, production, industry production share, coal

Table 3 Summary Statistics on Grids' Economic Factors 2001-2010

	N	Mean (S.D.)
GDP (10,000 yuan)	33,310	14,513,049.10 (177,147,695.94)
Primary GDP (10,000 yuan)	33,310	592,278.70 (2,802,789.00)
Population(person)	33,310	3,369,998.59 (21,686,072.20)
Urban (population > median)	33,470	0.06 (0.23)

Note: Standard deviations are in the parenthesis after the mean of the variables.

Table 4 Summary Statistics of Provincial Politicians 2001-2010

	N	Age	Political Age	Female (share)	Master or Higher Degree (share)	Home Province (share)
Secretary	781	56.09 (4.84)	32.17 (5.85)	0.03 (0.18)	0.46 (0.50)	0.27 (0.45)
Governor	390	57.80 (4.27)	32.52 (5.85)	0.02 (0.14)	0.49 (0.50)	0.24 (0.43)
Party Committee Member	2,418	56.22 (4.51)	31.69 (5.68)	0.07 (0.25)	0.45 (0.50)	0.31 (0.46)

Note: Standard deviations are in the parenthesis below the mean of the variables.

intensity for production, the number of employees, fuel has desulfurization (FGD) ability, and the natural log of all the variables above.The coefficients from the specification with natural log as dependent variable give us the effect of independent variables on the growth rate of variable of interest. $Treated_i$ indicates whether company i is treated. $After_t$ equals 0 from 2001 to 2005 and 1 from 2006 to 2010. ϕ_t represents the yearly fixed effect. η_i is the grid-level idiosyncratic error term. $\epsilon_{i,t}$ is the stochastic error term. The coefficient of the interaction term of treatment variable $Treated_i$ and time intervention variable $After_t$, α_3, indicates the treatment effect of the top-1,000 program. So that we can detect the impact of the program not only on local pollution but also on production, energy usage, market share, and clean technology adoption.

$$Outcome_{i,t} = \alpha_0 + \alpha_1 Treated_i + \alpha_2 After_t + \alpha_3 Treated_i \times After_t + \phi_t + \eta_i + \epsilon_{i,t} \quad (1)$$

Equation (2) sets up the model for event study at establishment level. α_k shows the difference in outcome variables, SO_2 and $log(SO_2)$, between the treated and the control from year 2001 to 2010. ϕ_t represents the yearly fixed effect. η_i is the grid-level idiosyncratic error term. $\epsilon_{i,t}$ is the stochastic error term. Model (2) helps us to find the treatment effect for each year.

$$Outcome_{i,t} = \alpha_0 + \alpha_1 Treated_i + \sum_{k=2001}^{2010} \alpha_k Treated_i \times Year_k + \phi_t + \eta_i + \epsilon_{i,t} \quad (2)$$

1.4.2 Spatial Analysis

Spatial analysis is based on the establishments' location, sulfur dioxide measurement, and grid-level converted control variables. The specifications in this paper for the grid-level analysis are difference-in-difference (DID) and triple-difference (DDD).

Equation (3) is the primary spatial analysis regression using a two-way fixed-effect model on a 10-year panel dataset. I count the number of treated and control establishments within a grid and use it as a weight for the model (3). The specification is only used for grids that contain treated or control establishments. The size of the grids is 0.625° by 0.5°, which is about 70 km by 55 km (or 43 miles by 35 miles).

Like the firm-level analysis, the comparison between treated and control should be on establishments with similar pre-treatment financial, energy usage, emission, production, etc. Therefore, I consider the matched treated and control establishments found in the firm analysis. Using the same specification model (3), the observations are only the matched establishments, and the weight is using the total number of matched treated and control establishments in a grid.

$$Octcome_{j,t} = \beta_0 + \beta_1 After_t + \beta_2 Treated_j + \beta_3 Treated_j \times After_t + X_{j,t} + v_t + u_j + e_{j,t} \quad (3)$$

In equation (3), $Outcome_{j,t}$ is the outcome variable at grid j in year t, which can be SO_2 surface concentration value and the natural log of that, $log(SO_2)$; $After_t$ is a dummy variable indicates whether it is after the year 2006 as it is the starting year of the program and the 11th five-year plan; $Treated_j$ is a dummy variable indicates whether treated establishment locates at grid j in year t; interaction term $Treated_j \times After_t$ means treated grid after 2006, and β_3 means the marginal effect of treated establishments on outcome variables; $X_{j,t}$ includes seven weather factors that affect pollution level at grid j at year t listed in Appendix Table A.1, county-level controls that include GDP, GDP for the primary industry, and population, integrated into grid-level. v_t represents yearly fixed effect. u_j is grid-level idiosyncratic error term. $e_{j,t}$ is the stochastic error term. In the following results section, we focus on the coefficient of the interaction term $Treated_j \times After_t$, β_3.

Using no-establishment grids as the baseline, equation (4) uses triple-difference design to find the marginal effect of control and treated establishments on local air pollution, SO_2, and its growth rate, $log(SO_2)$. $Control_j$ is the dummy variable for control grids. β_2 is the outcome difference between no-establishment grids and control grids before 2006. $Treated_j$ is the dummy variable for treated grids. β_3 is the outcome difference between no-establishment grids and treated grids before 2006. The coefficient for $Control_j \times After_t$, β_4, is the marginal difference of control grids after 2006. v_t represents yearly fixed effect. u_j is grid-level idiosyncratic error term. $e_{j,t}$ is the stochastic error term. The coefficient for $Treated_j \times Control_j \times After_t$, β_5, is the marginal treatment effect of treated grids on the outcome variables. Our focus in this model is β_5.

$$\begin{aligned} Octcome_{j,t} = \beta_0 + \beta_1 After_t + \beta_2 Control_j + \beta_3 Treated_j + \beta_4 Control_j \times After_t \\ + \beta_5 Treated_j \times Control_j \times After_t + X_{j,t} + v_t + u_j + e_{j,t} \end{aligned} \tag{4}$$

Equation (5) sets up the model for event study at grid level. β_k shows the difference in outcome variables between the treated and the control from year 2001 to 2010. v_t represents yearly fixed effect. u_j is grid-level idiosyncratic error term. $e_{j,t}$ is the stochastic error term. Event study can help us detect the yearly difference and see the change of trend after the treatment year 2006.

$$Outcome_{i,t} = \beta_0 + \beta_1 Treated_j + \sum_{k=2001}^{2010} \beta_k Treated_i \times Year_k + X_{j,t} + v_t + u_j + e_{j,t} \quad (5)$$

1.4.3 Spatial Production Analysis

Since the top-1,000 program targets the energy intensity of production, I use model (6) to find the marginal effect of production in the treated establishments. Model (6) is modified from model 4. The analysis is still conducted at the spatial grid level and weighted by total production of control and treated establishments in a grid.

$$\begin{aligned} Octcome_{j,t} = \gamma_0 + \gamma_1 After_t + \gamma_2 Treated\ Production_j \\ + \gamma_3 Treated\ Prodcution_j \times After_t + X_{j,t} + v_t + u_j + e_{j,t} \quad (6) \end{aligned}$$

In equation (6), $Treated\ Prodcution_j$ is the aggregated production from the treated establishments in grid j. γ_2 is effect of treated establishment production on outcome variables.The coefficient for the interaction term $Treated\ Prodcution_j \times After_t$, γ_3, shows the marginal effect of the treated production on outcome variables after 2006. Like previous spatial models, v_t represents yearly fixed effect. u_j is grid-level idiosyncratic error term. $e_{j,t}$ is the stochastic error term. If γ_3 is positive, the production at treated grids have higher SO_2 or $log(SO_2)$ per unit production, in this case, per 1,000 yuan.

1.4.4 Spatial Politician Analysis

To find the connection between environmental outcomes and politician characteristics, I use model (7) to disentangle the marginal effect of politician ages on outcome variables. Due to the limitation of data, we only look at the relationship between politician age and environmental outcome, while other politician characteristics are used as control variables. The politician analysis is an extension of the spatial analysis in section 1.4.2. Therefore, the specifications are at grid-level with ten years' panel data.

$$\begin{aligned} Octcome_{j,t} &= \delta_0 + \delta_1 After_t + \delta_2 Treated_j + \delta_3 Treated_j \times After_t \\ &\quad + \delta_4 Politician\ Age_{j,t} \times Treated_j \times After_t + X_{j,t} + v_t + u_j + e_{j,t} \end{aligned} \tag{7}$$

Based on model (3), model (7) include the independent variables $After_t$, $Treated_j$, $After_t \times Treated_j$, and the interaction term for politician characteristics, age, $After_t \times Treated_j \times Politician\ Age_{j,t}$. The variable $Politician\ Age_{j,t}$ includes the average age for provincial secretaries for the communist party and provincial governors. $X_{j,t}$ is a vector that includes grid-level control variables that include weather and economic factors and politician characteristics. The politician characteristics are average age, average party age[10], the share of higher than master's degree, the share of females, and share of home province politicians. $X_{j,t}$ contains characteristics for politicians such as provincial party secretaries, governors, and party committee members because they are the most influential politicians in a province, especially party committee members who make most decisions in a province. v_t represents

[10]Here "party" means China Communist Party.

the yearly fixed effect. u_j is the grid-level idiosyncratic error term. $e_{j,t}$ is the stochastic error term. The coefficient for $After_t \times Treated_j \times Politician\ Age_{j,t}$, δ_4, shows the marginal effect of one year average age increase in the local politician on air pollution SO_2, and its growth rate, $log(SO_2)$, in treated grids after 2006. If δ_4 is positive, that means higher local politicians' average age in the area leads to higher outcome variables and vice versa.

1.5 Results

Following empirical specifications, results are separated into four parts, the firm analysis results, spatial analysis results, spatial production results, and spatial politician results. Firm analysis results use model (1). Spatial results present tables from regressions based on the DID model (3) and the DDD model (4). Spatial production results section shows result from regression (6). Spatial politician results present regression results from equation (7).

1.5.1 Firm Analysis Results

The firm analysis uses the propensity score matching and difference-in-difference methodology. Table A.4 and Figure A.1 in the Appendix show that, before kernel matching, all the covariates, like financial, emission, energy, and production, are unbalanced. The raw sample indicates that treated companies are more prominent in production, generating, and emitting sulfur dioxide, total capital, employee numbers, etc. After propensity score matching, the treated and control establishments are balanced on almost all covariates except for production share in their industries.

Table 5 presents the difference-in-difference point estimated of the treated establishments on sulfur dioxide-related measurements, coal usage, production, and company size specifications. Compared to the matched control establishments, firms regulated by the top-1,000 program reduce less SO_2 and emit more sulfur dioxide, though their SO_2 generations do not show significant differences. Oddly, the treated establishments' FGD ability shows significant improvement after 2006. The treated establishments also use more coal, but no significant change in their production's coal intensity. Top-1,000 companies also produce more and have higher market production share in the industry, while the employee numbers decrease after 2006, compared to the control. It shows that the program doesn't reduce sulfur dioxide generation at the firm level, which implies there is no reduction in the usage of fossil fuels: coal. The results on sulfur dioxide generation and coal consumption are consistent. The effect on coal intensity also shows there is no significant signal that these treated establishments' production gets more efficient in terms of fossil fuel usage. The production and production share increase in treated establishments means that these establishments are market leaders after the treatment. The reduction in employee numbers shows a shrinkage of labor size on average in the treated establishments. But production and energy usage tell an expansion of capital and production. Combining all the results in table 5, we can say that there is no evidence showing that the top-1,000 program worked in terms of saving energy or reducing energy intensity.

Table 6 shows the result using the natural log of outcomes in table 5. The coefficients reported in table 6 are the point estimates of the increasing rate of outcome variables. The treatment effect of the program on the growth rates of SO_2 generation and SO_2 emission are positive and significant, while the effect on the growth rate of SO_2 reduction is insignificant. The effect on the growth rate of $FGDability$is insignificant. Combining those effects shows that the treated establishments generate and emit more SO_2 at an increasing rate while the reducing ability ofSO_2 is not getting stronger. Combining the positive coefficients in the $log(Coal)$ and $log(CoalIntensity)$ models shows that coal usage in treated establishments increases at an increasing rate in both quantity and production intensity. Comparing the results for production and employee numbers in table 5 and 6, the growth rate in production after 2006 in treated establishments doesn't have a clear trend. The decrease in employee sizes has slowed down over the years. Therefore, the effects of the top 1,000 program on establishments' sizes in labor and production are ambiguous. However, the share in the industry shows growth on an increasing trend in the treated.

Figure 4-7 shows the event study of the top-1,000 program treatment on sulfur dioxide emission, coal usage, production, and industry share of production between treated and control. The difference in sulfur dioxide emission shows a downtrend of positive difference, while the coal usage difference continues to surge positively. The difference in production and production share follow a similar trend. We can see both decreases from 2006 to 2007 but increase in 2008 and decrease afterward. Figure A.2-A.6 in the appendix show increases in the differences of SO_2 generation and reduction, no significant change in coal intensity, a first decrease and negative then increase employee number difference, and an increase and positive difference in FDG ability after 2006. Figure A.7-A.15 plot the average values and 95% confidence ranges of the outcomes in table 5. These graphs also support the results in event studies. The coefficients of the event study can be found in table A.5. The event study results on the growth rates are in table A.6. Coefficients from regressions in A.6 show a consistent pattern as the DID results in table 6.

Table 5 Firm Main Result

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	SO_2 Generation (ton)	SO_2 Reduction (ton)	SO_2 Emission (ton)	Coal (ton)	Production (1,000 yuan)	Production Share (percent)	Coal Intensity	Employee (person)	FGD Ability (kg hr-1)
Treated × After	121.9	-309.9*	349.2***	131254.1***	233401.9**	0.24***	0.15	-267.8***	1388.8***
	(201.7)	(161.3)	(82.6)	(6314.1)	(97098.0)	(0.070)	(0.47)	(35.7)	(418.9)
N	27,393	27,393	35,565	34,208	37,285	37,284	33,767	42,737	26,548

Notes: 1.The nine analyses all control for establishment and industry fixed effect.
2.Coefficients for variable "After" and "Treated" are omitted because of yearly and establishment level fixed effect.
3.Standard errors in parentheses.* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 6 Firm Increase Rate Result

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Log SO_2 Generation	Log SO_2 Reduction	Log SO_2 Emission	Log Coal	Log Production	Log Production Share	Log Coal Intensity	Log Employee	Log FGD Ability
Treated × After	0.13***	-0.046	0.11***	0.12***	-0.014	0.034*	0.13***	-0.056***	0.044
	(0.031)	(0.049)	(0.026)	(0.020)	(0.018)	(0.020)	(0.023)	(0.0076)	(0.064)
N	25,171	14,116	33,329	30,241	36,869	36,869	29,936	42,677	10,977

Notes: 1.The nine analyses all control for establishment and industry fixed effect.
2.Coefficients for variable "After" and "Treated" are omitted because of yearly and establishment level fixed effect.
3.Standard errors in parentheses.* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

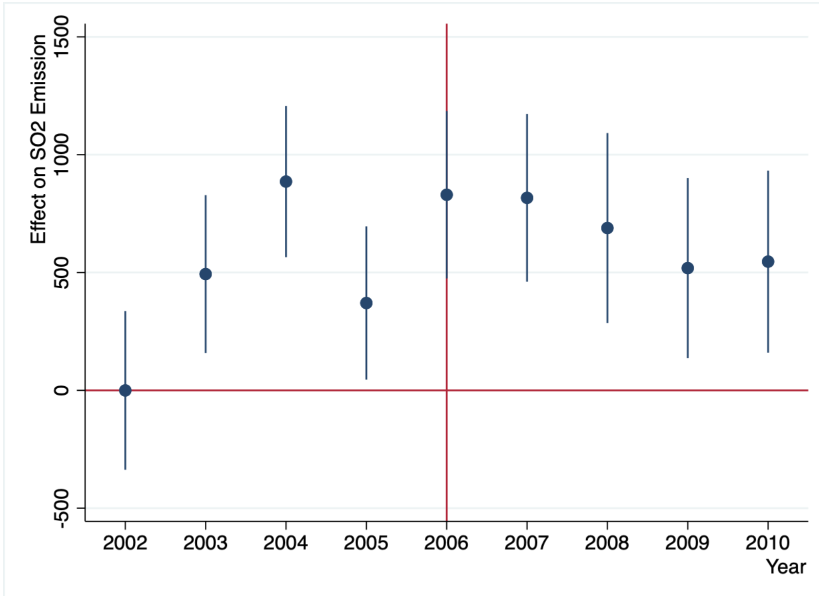

Figure 4 Event Study on Sulfur Dioxide Emission at Establishment Level

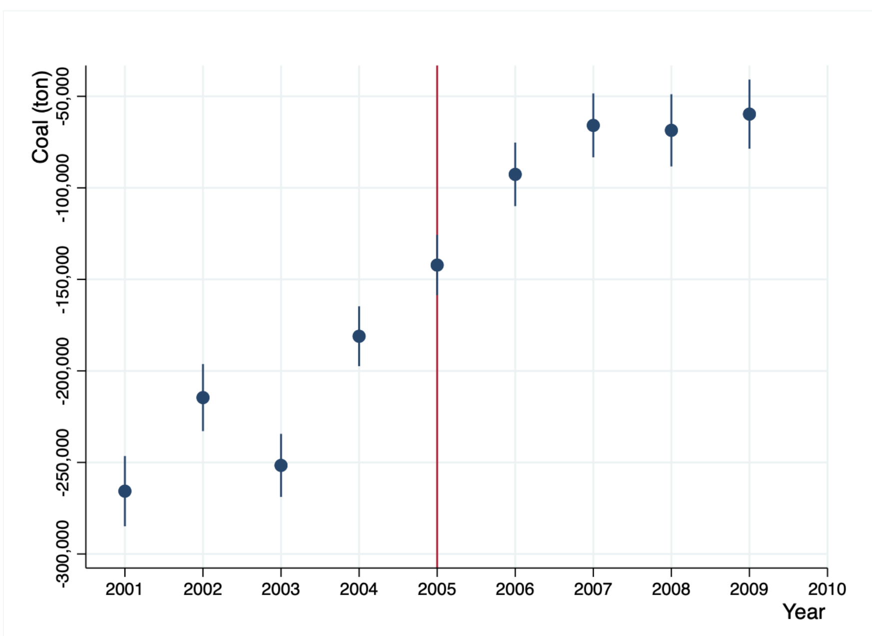

Figure 5 Event Study on Coal Usage at Establishment Level

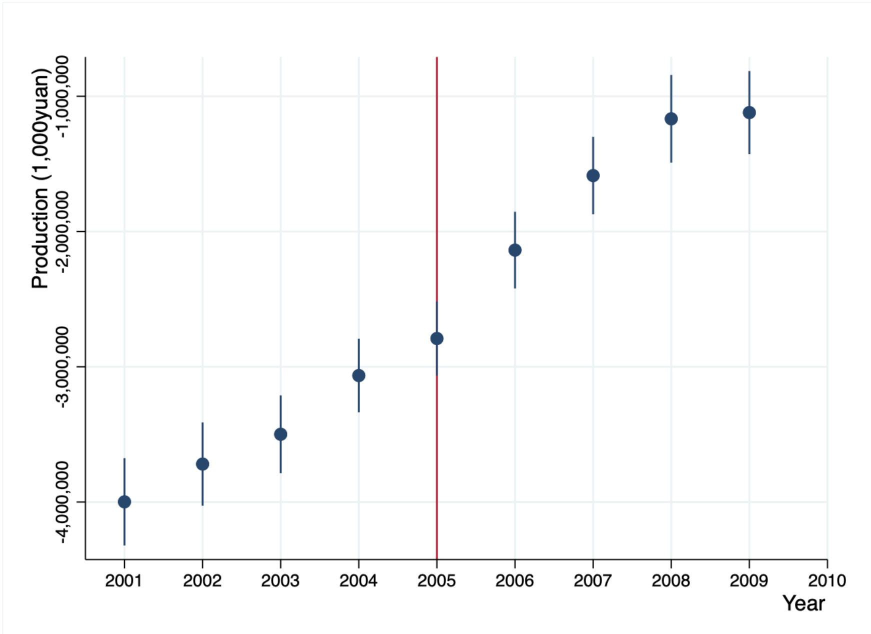

Figure 6 Event Study on Production at Establishment Level

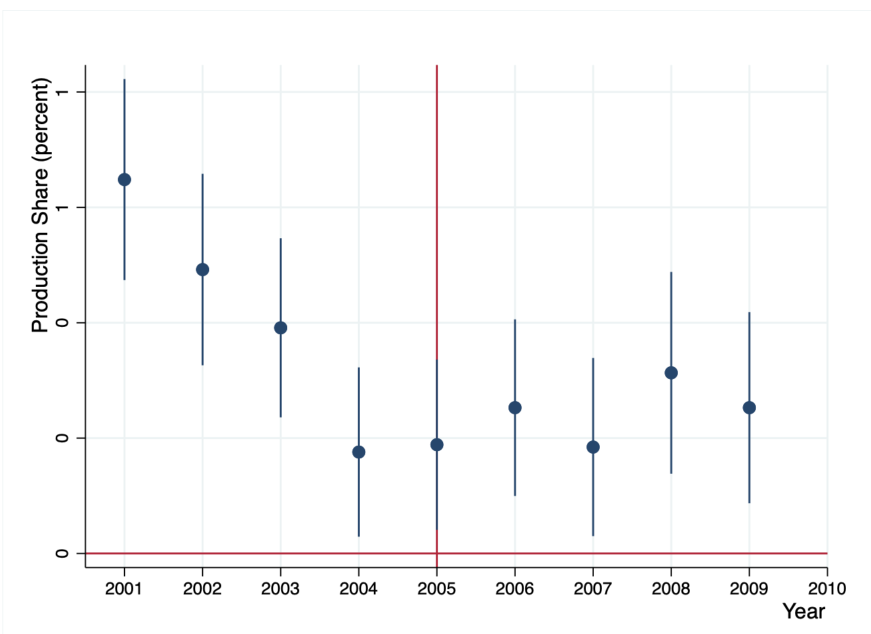

Figure 7 Event Study on Production Share at Establishment Level

1.5.2 Spatial Analysis Main Results

Table 7 is the main results at spatial grid level using model (3) on only the treated and control establishments sample. The outcome variables are SO_2 surface mass concentration annual average and $log(SO_2)$. Regressions are conducted on the raw sample with all treated and control establishments and the matched sample. Column (1) and (3) use all observation, and column (2) and (4) use only the matched sample. Table 7 column (1) and (2) use the raw values of SO_2 as outcomes, while column (3) and (4) use $log(SO_2)$ to find the effect of treated establishments on the growth rate of SO_2 . Table 7 shows that treated grids have 2.38 kg km-2 higher SO_2 on average than the control grids at a 99% significance level in unmatched sample. But the growth rate of SO_2 is lower than the control grids. In the matched sample, the difference between treated and control grids after 2006 is smaller than the full sample but still positive and significant. But the treatment effect on growth rate in the matched sample is smaller and insignificant.

Table 7 tells a slightly different story from the firm study result table 5. Instead of increasing emission at an increasing rate at the establishment level, grid-level analysis shows an increasing emission at an insignificant decreasing rate for the treated grids. But based on the matched sample analysis, we cannot say the treated establishments slow down their emissions after 2006.

Table 8 is the result for the DDD model (4) using no-establishment grids as baseline. Like table 7, column (1) and (3) are results for the full sample where the control and treated establishments locate, while column (2) and (4) are results for the grids with matched establishments. Outcome variables are SO_2 and the growth rate of it, $log(SO_2)$. From column

(1) and (2) in table 8, we can say that the treated grids have higher concentration of SO_2 after 2006. Columns (3) and (4) indicate that the growth rate of SO_2 come down after 2006. Unlike column (4) in table 7, the negative coefficient on $After \times Control \times Treated$ is significant and has higher magnitude than column (3), the all sample regression. However, since the DDD specification does not use the weight used in DID specification, the difference in table 7 and 8 is expectable.

Figure 8 shows the event study results of the treated grids on SO_2 levels. Figure 9 shows the event study results of the treated grids on the growth rate of SO_2. The two figures present a negative difference between the treated and control grids before the treatment and approaches zero in 2006. But the difference keeps increasing after 2006 until 2009 and drop afterward.

1.5.3 Spatial Production Analysis Results

Tables 9 shows the effect of the aggregated production of treated companies at grid level on sulfur dioxide using model (6). The columns are similar to table 7. The results for SO_2 and $log(SO_2)$ using grids with all control and treated establishments show that, after 2006, the production from treated establishments emits more SO_2 than the control. But the impact of production on the growth rate of SO_2 is negative, meaning the SO_2 emission per production declines. When we only include matched sample, the difference between control production and the treated becomes insignificant. But the decline in $log(SO_2)$ is larger and still significant. Combining table 7, 8, and9, we can say that the production level of treated grids increase at a decreasing rate after the launch of the top 1,000 program. While its emission intensity from the production has not changed and shows a decreasing growth rate.

Table 7 Spatial Main Result

	(1)	(2)	(3)	(4)
Dependent Variable	SO_2		$\log(SO_2)$	
Sample	All	Matched	All	Matched
Treated	-1.07***	-1.26***	0.0047	0.0024
	(0.16)	(0.18)	(0.0034)	(0.0036)
After× Treated	2.38***	1.95***	-0.012***	-0.0005
	(0.13)	(0.16)	(0.0027)	(0.0031)
Controls	Yes	Yes	Yes	Yes
Observations	10,138	7,824	10,138	7,824

Notes: 1. Controls in the analysis including grid level economic factors and weather characteristics.
2. All models include grid and year levels fixed effects.
3. Standard errors in parentheses.
4. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

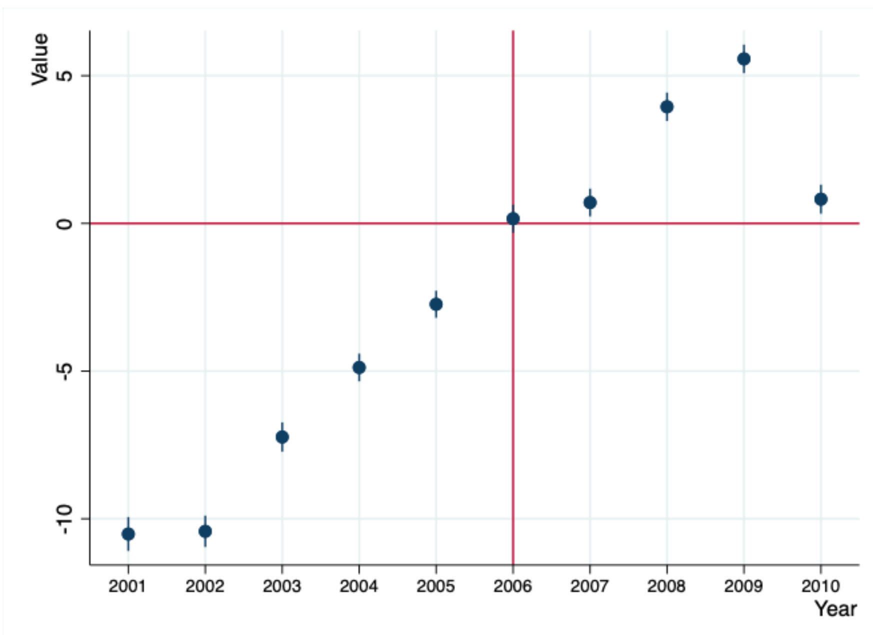

Figure 8 Event Study for the Effect of Treatment on SO_2

Table 8 Spatial Main Result with No Establishment Grids as Baseline

	(1)	(2)	(3)	(4)
Dependent Variable	SO_2		$\log(SO_2)$	
Sample	All	Matched	All	Matched
Control	-1.60***	-1.45***	0.0048	0.011**
	(0.060)	(0.072)	(0.0044)	(0.0050)
Treated	-0.98***	-1.26***	0.018**	0.018***
	(0.090)	(0.10)	(0.0066)	(0.0064)
After×Control	3.95***	4.09***	0.10***	0.094***
	(0.053)	(0.059)	(0.0039)	(0.0042)
After×Control×Treated	2.22***	1.58***	-0.017*	-0.019***
	(0.080)	(0.095)	(0.0059)	(0.0068)
Controls	Yes	Yes	Yes	Yes
Observations	33,220	33,220	33,220	33,220

Notes: 1. Controls in the analysis including grid level economic factors and weather characteristics.
2. All models include grid and year levels fixed effects.
3. Standard errors in parentheses.
4. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Figure 9 Event Study for the Effect of Treatment on Log(SO_2)

Table 9 Spatial Main Result with Production

	(1)	(2)	(3)	(4)
Dependent Variable	SO_2		log(SO_2)	
Sample	All	Matched	All	Matched
Production of Treated	-2.2e-09***	-2.2e-10	9.5e-12**	7.9e-11***
	(2.7e-10)	(1.4e-09)	(4.5e-12)	(2.3e-11)
After × Production of Treated	3.1e-09***	1.1e-09	-1.4e-11***	-7.2e-11***
	(2.6e-10)	(1.4e-09)	(4.4e-12)	(2.3e-11)
Controls & Fixed Effects	Yes	Yes	Yes	Yes
Observations	8,645	2,334	8,645	2,334

Notes: 1. Controls in the analysis including grid level economic factors and weather characteristics.
2. All models include grid and year levels fixed effects.
3. Standard errors in parentheses.
4. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

1.5.4 Spatial Politician Analysis Results

Table 10 shows the heterogeneous treatment effect of politicians' average age in the top-1,000 program on air quality and its change using model (7). The table shows the effect of the average age of two political positions, China Communist Party (CCP) secretary and provincial governor. Like previous tables, the first two columns use SO_2 as the dependent variable, while the last two columns use $log(SO_2)$. Columns (1) and (3) use Secretary Average Age for the politician interaction term, while columns (2) and (4) use Governor Average Age. All four regressions have provincial politician characteristics as control variables, including the average age, average political age, the female share of politicians, etc., for provincial party secretaries, governors, and party committee members. The coefficients of $After \times Treated \times Secretary\ Average\ Age$ are positive and significant for both outcome variable SO_2 and $log(SO_2)$. While $After \times Treated \times Governor\ Average\ Age$'s coefficients are negative on SO_2 but positive on $log(SO_2)$. Higher provincial party secretaries are associated with higher pollution and positive growth rates on the pollution level. Higher governor age is associated with lower pollution levels, and the negative effect gets higher after 2006. The coefficients on Secretary Average Age and Governor Average Age are positive and significant, indicating that older politicians are associated with higher pollution levels. With $log(SO_2)$ being the outcome, Secretary Average Age has no significant impact on the changing rate of SO_2. But Governor Average Age has a positive impact on it.

The result is consistent with the literature that governors tend to be held accountable for local economic growth and policy implementation performance in China. Party secretaries are more responsible for administrative and party work. Chinese politicians are more motivated by preventing political demotion than seeking promotion in the case of compliance with environmental regulations. Older politicians have more pressure and motivation to preserve their reputations before retirement. Therefore, higher age is associated with more reduction in SO_2 and a higher change rate.

1.6 Conclusion

The top-1,000 program rolled out in 2006 along with the 11th five-year plan was the largest scaled energy-saving program in history. Committed to sustainable growth and less reliance on fossil fuels on the international stage, the Chinese government was under pressure to deliver plausible energy reduction since 2005. This paper not only evaluates the compliance outcome of the energy-saving program but also answers the question of whether saving energy means less pollution and a better environment.

Empirical results from both the firm and grid analysis show that, the establishments belongs to the firms in top 1,000 program experienced an increase in energy usage, production, and pollution emission. There is no significant change in the energy intensity of production. But after the rollout of the program, the growth rate of local pollutant SO_2 declined after 2006. When we consider the age of provincial politicians, higher governor's average age in a grid is associated with lower local air pollution level at a higher growth rate.

There are a few drawbacks in the design of the program as discussed by previous research, such as relative measures, other than absolute measures, in initial target setting, self-reporting procedure in the evaluation of target achievement, and setting low targets for easy achievements. Both firm-level and spatial-level two-way fixed effect model do not show

Table 10 Politician Result on Treated and Control Establishments Sample

	(1)	(2)	(3)	(4)
Dependent Variable	SO_2		$\log(SO_2)$	
Interaction Term	Secretary	Governor	Secretary	Governor
Treated	-1.32***	-1.28***	-0.0023	-0.0022
	(0.15)	(0.15)	(0.0035)	(0.0035)
After × Treated	-2.44**	11.0***	-0.071***	-0.098***
	(1.21)	(1.11)	(0.027)	(0.025)
Secretary Average Age	0.23***	0.24***	-0.00024	0.00024
	(0.021)	(0.019)	(0.00047)	(0.00044)
Governor Average Age	0.30***	0.35***	0.0043***	0.0037***
	(0.016)	(0.017)	(0.00037)	(0.00040)
After × Treated × Secretary Average Age	0.084***		0.0012**	
	(0.021)		(0.00047)	
After × Treated × Governor Average Age		-0.15***		0.0016***
		(0.019)		(0.00043)
Observations	8,013	8,013	8,013	8,013

Notes: 1. Controls in the analysis including grid level economic factors, weather characteristics, and politician characteristics.

2. All models include grid and year levels fixed effects.

3. Standard errors in parentheses.

4. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

the positive impact of the top-1,000 program on sulfur dioxide reduction. Even though the number of employees decreased from 2006 to 2010 compared to the control establishment, we can still see a significant production growth in the treated establishments and an increase in industry share. We can also see a significant improvement in the treated establishments' FGD ability. It indicates that the treated companies invested more in capital input rather than labor input and likely kept their industry leader roles.

Possible explanation for the firm level increase in coal usage and the over-compliance public report from the top-1,000 energy-saving program is misreporting of the program reports. Given that the program requires companies to report energy saving, not energy usage, to the public, trying to find the exact result of this program is difficult.

Targets need to be clear. The program aims at save energy considering economic growth. Therefore, the design of the target is based on energy saved per GDP growth. This number is hard to calculate, interpret, and evaluate. It would be better for policy maker to set absolute targets.

1.7 Future Research

Future research includes first adding political research at the firm level. I can match the location of the establishments with local politician characteristics. To utilize firm locations more in spatial analysis, one can use surrounding areas of establishments for the research unit as an alternative. Urban and rural area heterogeneity research should be discussed. To find out why we don't see a promising result on reducing sulfur or coal, we can investigate more industrial companies that are related to the treated companies in finance or products but not in the top 1,000 programs.

Chapter 2 Location choice of Air quality monitors in China

2.1 Introduction

The World Health Organization estimated that, in 2016, air pollution killed seven million people, of which over four million were due to ambient air pollution. In addition, millions of people are diagnosed with respiratory diseases each year. As a result, air pollution is one of the most significant public health concerns today. One-way countries have begun to tackle air pollution is through air quality monitoring via pollution monitors. These monitors provide valuable information to the public and government agencies to tackle ambient air pollution.

The public can use pollution information to curb their daily behavior, such as going out during less polluted times, installing air purifiers, spending less time outdoors during the high level of air pollution, purchasing higher quality masks, etc. Barwick et al., 2019 show that expanding public access to air pollution data in China resulted in an increase in people searching for pollution- related topics online, altering consumption patterns to avoid pollution exposure, and higher willingness to pay for houses in less polluted areas. In addition, people can also use this information to pressure local and central governments to tackle the air pollution at the source. Local and central governments can use pollution information to guide the public in certain behaviors and bring out policies to curb air pollution.

Figure 10 from 2019 shows that air quality monitors are most common in the United States, Western Europe, and East Asia. China is one of the countries in East Asia that is rapidly increasing pollution monitoring. Since 2013-14, China has added more than five thousand air quality monitoring stations that provide real-time information. These mon-

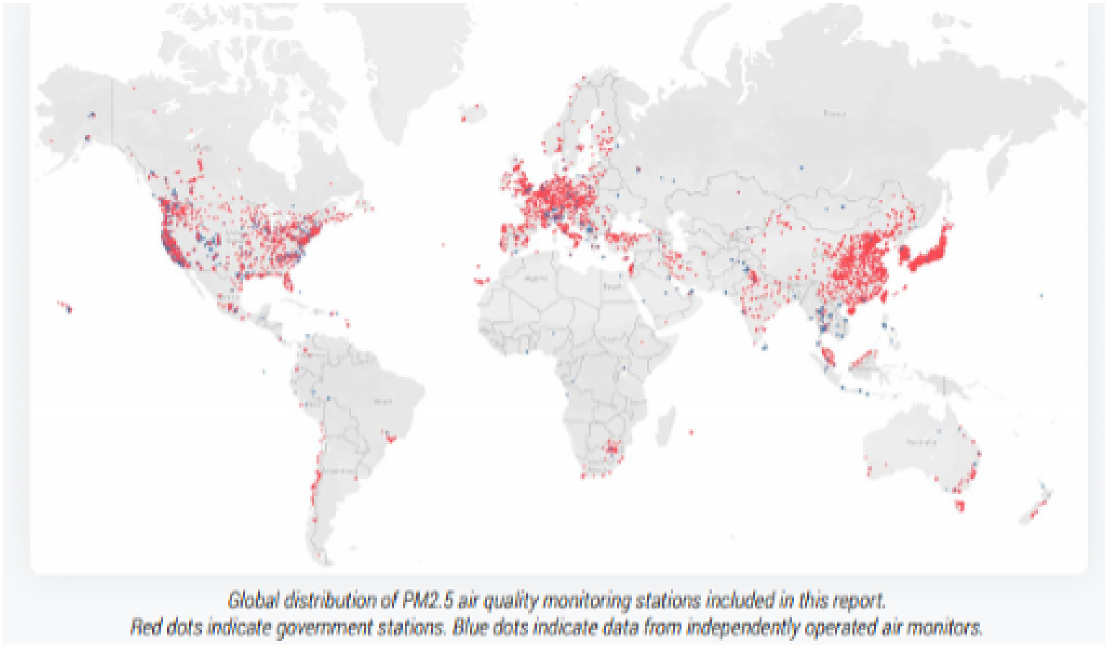

Figure 10 Map from IQ Air 2019 World Air Quality Report

itoring stations give information to the public on six airborne pollutants, namely PM2.5, PM10, sulfur dioxide, nitrogen dioxide, ozone, and carbon monoxide. Authorities manage these monitors at four levels of the government: state, provincial, municipal, and county. Table 1 shows the entry and exit of central and local air quality monitors from 2013 to 2021. While there was an initial influx of monitors controlled by the central government, local governments have been actively placing new monitors in recent years. However, we have very little empirical evidence on why the government chooses a particular location to place these monitors.

Governments can place air quality monitors for various reasons. First, the government may want to protect children and patients by locating pollution monitors closer to schools and hospitals to give accurate information to these vulnerable populations. Another reason can be to monitor road traffic pollution as automobiles constitute a significant source of pollution. Likewise, they may also place monitors near polluting industries to accurately assess the impacts of pollution. In addition, local governments may have other incentives to place monitors in strategic locations. First, the state government might punish officials in provinces/cities/counties with bad air quality[11]. Second, as the air quality data is openly available, there may be public pressure for officials to improve the air quality[12]. Previous literature has shown that there are incentives for local governments to misbehave and locate monitors in strategic locations. Grainger et al., 2016 find that counties that are marginal to the non-attainment threshold for National Ambient Air Quality Standards (NAAQS) placed newly sited monitors in cleaner areas relative to counties non- marginal in the US. Furthermore, local governments can encourage production in polluting firms to collect tax revenue and promote economic growth (Qi & Zhang, 2014).

In this paper, we try to find the parameters that explain the location choice of air pollution monitors. Our project will be one of the first to explore the government's behavior in placing pollution monitors in developing countries. The 2013-14 monitoring and disclosure program was hailed as a national success by the Chinese government in providing accurate air quality information to the public. However, where the governments place the monitors strongly affects the pollution readings. Therefore, it is essential to study the factors that go into the government's decision-making in choosing the location for the air quality monitors.

[11] Previous research on environmental policy (Kahn et al., 2015) in China suggests that central government often uses policy achievement as a tool to evaluate local government officials.

[12] See Xu et al., 2019 to learn about the progress of environmental activism in China and how Chinese NGOs involved in the air quality measurement activities use social media and other communication methods to fulfill their organizational objectives and connect fragmented supportive forces.

2.2 Literature

Previous literature on location choice factors is sparse and limited to fields outside of economics, like geology. Yu et al., 2018 found that air quality monitoring stations were clustered around high pollution areas in the Beijing-Tianjin-Hebei area in China. is a closely related paper to ours. They study the factors affecting the addition of a monitor, the retirement of a monitor, and the year-to-year changes in the number of monitors. Using ozone (O_3) as their measure of pollutant, they found that peak O3 readings in the previous period significantly affected the addition or removal of the air quality monitor. Yang et al., 2020 studied the staggered roll-out of central monitors in China and found significant impact on local air quality surrounding the monitors, not elsewhere.

Another question yet to be answered is the optimal location of the air pollution monitors. Some geological studies study the optimization of monitoring networks (Haas, 1992; Lu et al., 2011; Maji et al., 2017; Pires et al., 2008). Although these studies consider some economic and social variables like population density, land use, and the city's size, they are not comprehensive.

Our paper fills the gap of literature in monitor location choice in China. We look at both current monitors and monitor additions in the past few years. Considering possible economic, demographic and infrastructure features, we try to give a full picture of understanding the air quality monitoring system in China.

2.3 Data

2.3.1 Monitor location

We use the monitor location data gathered from individual province websites and the central government website, where the pollution data is made public. The data was made available by Shanghaiqingyue (http://data.epmap.org/), which is an organization that focuses on the publicity of environmental data and promoting scientific research. The data covers around 1,481 central government-controlled monitors and 2,200 local government-controlled monitors in 2021[13]. Figure B.1 and B.2 show the current (2021) location of central and local monitors in China with air pollutant P.M. 2.5 level as backgrounds. Table 11 shows the entry and exit of central and local monitors from 2013 to 2021. While the initial influx of monitors was mainly central monitors, a lot more local monitors were added to the monitoring grid system in recent years. The growing number highlights the significance of local monitors in providing air quality information to the public.

2.3.2 Pollution Data

We use satellite pollution data from Xu et al., 2019 and Van Donkelaar et al., 2016. Their estimates of PM 2.5 are based on an empirical model which includes just the satellite Aerosol optical depth (AOD)[14] measurement at $0.05° \times 0.05°$ resolution[15]. The raw satellite AOD data comes from NASA's Moderate Resolution Imaging Spectro-radiometer (MODIS). Fig-

[13]Due to limited data availability, the local data only covers twenty-four provinces out of thirty-one provinces in China.

[14]Aerosol optical depth is a measure of the extinction of the solar beam by dust and haze. In other words, particles in the atmosphere (dust, smoke, pollution) can block sunlight by absorbing or by scattering light. AOD tells us how much direct sunlight is prevented from reaching the ground by these aerosol particles. It is a dimensionless number that is related to the amount of aerosol in the vertical column of atmosphere over the observation location.

[15]The $0.05° \times 0.05°$ resolution can be understood roughly as a 5km-by-5km spatial grid cell.

Table 11 Entry and Exit of Air Quality Monitors (2013-2021)

	Central Monitors		Local Monitors	
Year	Entry	Exit	Entry	Exit
2013	701			
2014	209	1	22	
2015	390	27	408	
2016	36	38	291	14
2017	36	33	495	18
2018	25	23	143	45
2019	14	15	394	31
2020	37	85	842	370
2021	323		271	
Total	1,771	222	2,866	478

ure 11 shows the level P.M. 2.5 in 2018 across the country. Beside the desert in Xinjiang province, the northeast part of China had the highest pollution, mostly around Hebei, Henan, Shandong, Beijing and Tianjin provinces.

2.3.3 Other Variables

For our control variables, we collect the gross domestic product (GDP), GDP for primary industries, government revenue, the number of large companies, and the number of high school students at the county level from China Statistical Yearbooks. In addition, we scrape school and hospital location data from the Gaode map, a Chinese version of Google maps. The length of primary highway is gathered from open street maps (OpenStreetMap contributors,

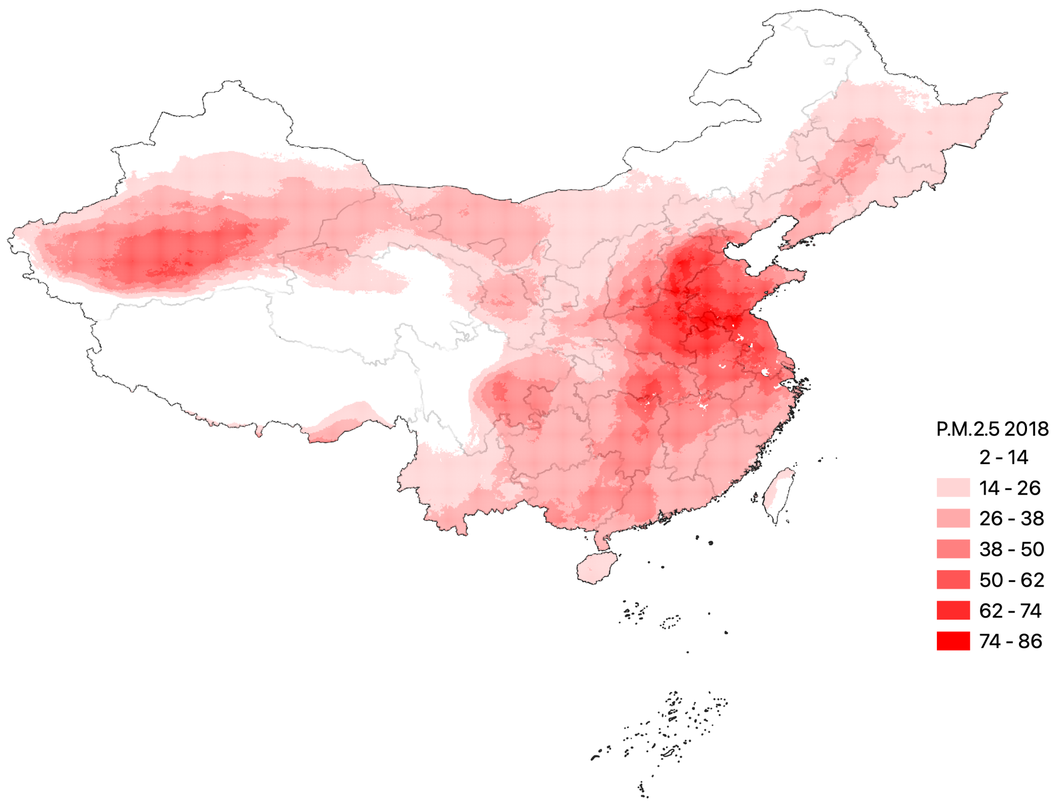

Figure 11 Map from IQ Air 2019 World Air Quality Report

2017). Population density is from census 1km estimates in 2010, 2015 and 2020. The other years of population density are interpolated using linear estimates.

Summary statistics for 2021 are presented in Tables 12 and 13. Table 12 provides the summary statistics for central monitor analysis, and Table 13 provides summary statistics for local monitor analysis. The summary statistics show that local monitors are placed in polluted areas more than central monitors on average. One explanation for this discrepancy can be that the authorities clean up areas around the monitors once the monitor is placed there. Since most of the central monitors were placed in earlier years, from 2013 to 2015, areas around the monitors are already cleaned, hence the lower average PM 2.5. A recent paper, Yang et al., 2020, found that local governments targeted pollution reductions in areas closer to the monitors after the monitor installation.

Another explanation can be that central monitors are installed in areas where there are fewer people, less economic activity, and as a result, lower pollution levels. The summary statistics give a good indication of this theory. In almost all metrics of population, infrastructure, and economic activity, local monitors are installed in grids with denser population and more significant economic activity on average. It can also be explained by the fact that we only have local monitor data for 22 provinces in China, and most of them are highly populated.

Table 12 Summary Statistics for Central Monitor Data in 2021

Variable	N	Mean	S.D.
Central Monitor Dummy	385,567	0.004	0.062
Average P.M. 2.5	385,567	29.41	21.02
Length of Highway	385,567	964.04	3,348.477
Population Density	385,567	145.15	726.198
Number of Schools	385,567	0.54	3.112
Number of Hospitals	385,567	0.15	1.486
Distance to the Nearest Central Monitor	385,567	1.31	1.227
Distance to the Nearest Local Monitor	385,567	3.61	4.769
GDP	381,378	43,250.39	8.28E+05
GDP of Primary Industry	381,355	57,191.49	1.63E+06
Government Budget Revenue	381,378	2,462.84	1.24E+05
Number of Large Companies	338,090	1.46	19.715
Number of High School Students	381,378	233.68	2564.662

Table 13 Summary Statistics for Local Monitor Data in 2021

Variable	N	Mean	S.D.
Local Monitor Dummy	228,569	0.01	0.097
Average P.M. 2.5	228,569	33.40	22.545
Length of Highway	228,569	1,331.48	4020.82
Population Density	228,569	215.80	896.349
Number of Schools	228,569	0.83	3.875
Number of Hospitals	228,569	0.23	1.783
Distance to the Nearest Central Monitor	228,569	0.98	0.961
Distance to the Nearest Local Monitor	228,569	0.87	0.992
GDP	225,625	66,259.06	9.49E+05
GDP of Primary Industry	225,625	91,737.91	2.10E+06
Government Budget Revenue	225,625	3,672.16	1.36E+05
Number of Large Companies	212,123	2.20	24.209
Number of High School Students	225,625	354.14	3175.171

2.4 Methodology

We first construct approximately a 5-kilometer by 5-kilometer grid for all of China for our study. As shown in figure 12 below, there are some grids where the pollution monitors are located, and there are no pollution monitors in others. We then conduct two sets of analyses. First, we do a cross-section analysis of the current pollution monitors (in 2021). Then, we analyze what factors affect the location choice for air quality monitors. We also differentiate the analysis for central and local monitors.

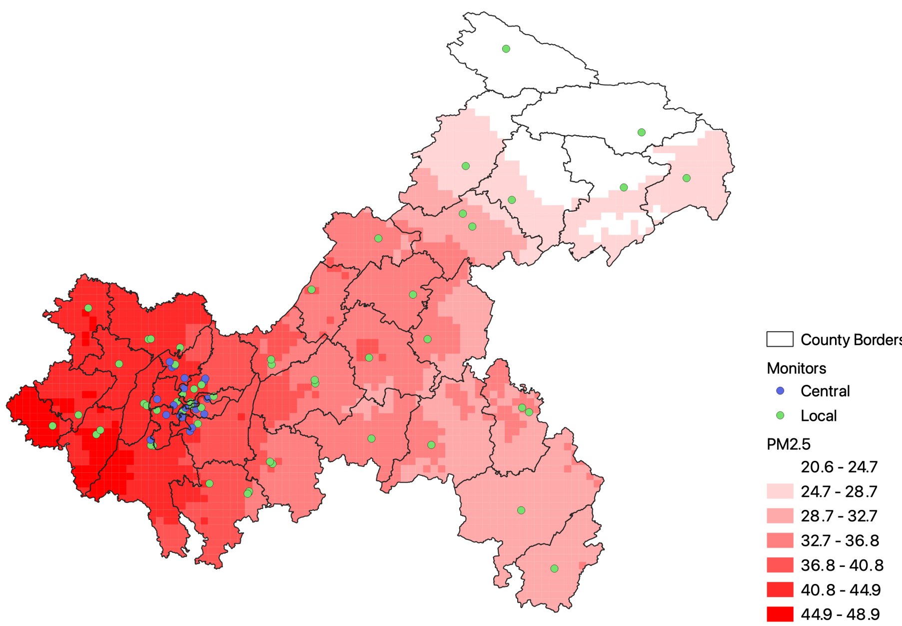

Figure 12 Chongqing City PM2.5 (2018) and Monitor Location (2021)

2.4.1 Where are the monitors located?

To study where the monitors are located currently, we estimate the following cross-section logit model, one each for central and local monitors, where our outcome is a binary variable;

1 if there is a pollution monitor within the grid, 0 if the grid does not have a pollution monitor.

$$Pr(Monitor_i = 1|X_i) = \phi(\alpha + \beta_1 PM2.5_i + \beta_2 Controls_i + u_i) \tag{8}$$

The explanatory variable $Pr(Monitor_i = 1|X_i)$ is whether grid i has at least one monitor. $\phi()$ is the function form of logistic model. $PM2.5_i$ is average P.M. 2.5 at grid i from 2011 to 2018. $Controls_i$ represents control variables for grid i. Control variables include population density, length of the highway within the grid, number of schools and hospitals in the grid, distance to the nearest central monitor, distance to the closest local monitor, gross domestic product (GDP), GDP of primary industries, government revenue, number of large companies, and number of high school students. Finally, u_i is the error term. We cluster standard error at the county level for all analyses and control provincial level fixed effect for some analysis.

2.4.2 What influences the location choice?

To study the factors influencing the location choice of monitors, we estimate the following panel logit model, one each for central and local monitors.

$$Pr(New\ Monitor_{i,t} = 1|X_{i,t-1}) = \phi(\beta_0 + \beta_1 P.M.2.5_{i,t-1} + \beta_2 Controls_{i,t-1} + u_i + \sigma_t + \epsilon_{i,t}) \tag{9}$$

The explanatory variable $Pr(NewMonitor_{i,t} = 1|X_{i,t-1})$ is whether grid i at time t-1 has at least one pollution monitor. $P.M.2.5_{i,t-1}$ is P.M. 2.5 value at grid i and time t-1. $Controls_{i,t-1}$ represents control variables for grid i at time t-1. Control variables include population density, length of the highway within the grid, number of schools and hospitals in the grid, distance to the nearest central monitor, distance to the closest local monitor, gross domestic product (GDP), GDP of primary industries, government revenue, number of large companies, and number of high school students. We control for time-invariant location and year fixed effect through u_i and σ_t respectively. Finally, $\epsilon_{i,t}$ is the error term. We cluster standard error at the county level for all analyses and control provincial level fixed effect for some analysis. The coefficient β_1 is our focus. It tells us how likely the government places monitor at a more polluted grid.

2.5 Results

We are presenting two tables for our main results. Table 14 shows the cross-section analysis of the monitors currently located with and without province fixed effect. Table 15 is a yearly analysis of an entry of a new monitor in a grid cell with and without province fixed effect. Both table 4 and 5 use standardized explanatory variables for the convenience of result interpretation.

2.5.1 Where are the monitors located?

In Table 14, columns (1) and (2) are the marginal effect from logit regressions for central monitors only, and Columns (3) and (4) are the marginal effect from logit regressions for local monitors only. Similarly, columns (1) and (3) do not include province fixed effect, and columns (2) and (4) include province fixed effect. Although not statistically significant, the results suggest that central monitors are likely to be in grids with lower P.M. 2.5 and local monitors are likely to be in grids with higher P.M. 2.5. However, the negative coefficients on population density and length of highways imply that local monitors are installed away from densely populated areas and major highways. Hence, it is likely that areas around the central monitors were cleaned up in the years following the installation.

The results also indicate that both central and local monitors are in grids with a greater number of schools and hospitals. Distance to the nearest local monitor is negatively related to the location of the central monitor. Economic indicators such as GDP, GDP of primary industries, and Government revenue have mixed effects on installing a local or central monitor. Whether controlling for province fixed effect or not has a significant impact on the marginal effects of average P.M. 2.5, though the effects are insignificant. Table B.1 in the appendix is the linear probability results for central and local monitor models. It shows significant marginal effects of the level of pollution on whether a grid has central or local monitors. Central monitors tend to locate in cleaner grids than local monitors in 2021. The linear regressions are all controlled for province fixed effect.

2.5.2 What influences the location choice?

Table 15 shows the results from our panel data analysis of installing a new central or local monitor in a grid cell. We conduct separate analyses for central and local monitors presented in columns (1) and (2) and columns (3) and (4), respectively. In this analysis, we lag our explanatory variables by one year. We assume that the government will consider historical air pollution measures and other factors in choosing a location to install a monitor. Our results indicate that central monitors are installed in relatively more polluted areas, whereas local monitors are installed in cleaner areas.

The negative coefficients on the number of large companies and high school students

Table 14 Marginal Effects for Monitor Location in 2021 Using Logit Models

	(1)	(2)	(3)	(4)
	Central Monitor		Local Monitor	
Average P.M. 2.5	-0.0048	-0.037	0.0011	0.0059
	(0.0030)	(0.025)	(0.0025)	(0.0052)
Length of Highway	-0.000068	-0.00055	-0.0012*	-0.0031*
	(0.00068)	(0.0017)	(0.00074)	(0.0016)
Population Density	0.00055	-0.00017	-0.0010*	-0.00023
	(0.00096)	(0.0021)	(0.00054)	(0.0014)
Number of Schools	0.00045	0.0024	0.0014	0.0021
	(0.00081)	(0.0027)	(0.0012)	(0.0030)
Number of Hospitals	0.00014	-0.00048	0.0023	0.0040
	(0.00050)	(0.0015)	(0.0014)	(0.0026)
Distance to the Nearest Central Monitor			0.0021	-0.00063
			(0.0046)	(0.012)
Distance to the Nearest Local Monitor	-0.0093*	-0.064**		
	(0.0048)	(0.027)		
GDP	0.0014	0.0032	-0.0016	-0.0054
	(0.0045)	(0.011)	(0.0015)	(0.0035)
GDP of Primary Industries	-0.00074	-0.0025	0.00098	0.00072
	(0.0015)	(0.0041)	(0.0031)	(0.0029)
Government Revenue	-0.00051	-0.0028	-0.00014	0.0013
	(0.0016)	(0.0053)	(0.00079)	(0.0016)
Number of Large Companies	-0.000014	0.0016	0.0016	0.0024
	(0.0016)	(0.0040)	(0.0016)	(0.0041)
Number of High School Students	0.00016	0.0023	0.00035**	0.0025**
	(0.00010)	(0.0021)	(0.00017)	(0.0010)
N	1,492	633	2,185	1,062

Notes: 1. All explanatory variables are standardized.
2. Standard errors in parentheses.
3. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

suggest that local monitors are not limited to dense urban areas but spread around the smaller cities or rural areas. The significant positive correlation of local monitor with distance to nearest local monitor indicates that local monitors are installed near each other. One interesting common result between central and local monitors is that the coefficients on the number of large companies are all negative and significant in the case of local monitors. It seems like both the local and central governments are focused on providing pollution information on where people live and not where people work. While this might be beneficial to people who work from home, it may not benefit those who have to go to the physical site. Like the cross-sectional analysis, controlling for province fixed effects make a difference on the results. But the central and local monitor results react opposite to this change.

Adding fixed effects almost make all variables less effective in location choice of central monitors, which means provincial fixed effect could explain more of the differences in location choice than the independent variables, though all of them are insignificant in choosing a new monitor location. However, adding provincial fixed effects makes the lagged P.M. 2.5 more effective and significant, while the effect of other factors become smaller. The negative marginal effects from the lagged P.M. 2.5 indicates that local governments may avoid dirty areas when they install new monitors, though the performance of those monitors do not determine their political careers.

Table 15 Marginal Effects for Monitor Location in 2021 Using Logit Models

	(1)	(2)	(3)	(4)
	Central Monitor		Local Monitor	
L.P.M. 2.5	0.0035	0.0023	-0.030	-0.084***
	(0.0061)	(0.0028)	(0.035)	(0.030)
L.Length of Highway	-0.000068	-0.000027	0.0095**	0.0053*
	(0.00016)	(0.000090)	(0.0038)	(0.0031)
L.Population Density	0.0019	-0.0014	-0.0092	-0.024
	(0.0027)	(0.00099)	(0.046)	(0.019)
L.Distance to the Nearest Central Monitor	0.058	0.017	0.016	0.013
	(0.10)	(0.015)	(0.079)	(0.040)
L.Distance to the Nearest Local Monitor	0.00061	0.00080	0.074***	0.039**
	(0.0013)	(0.0011)	(0.015)	(0.016)
L.GDP	0.0012	0.0019	0.078	0.050
	(0.0015)	(0.0026)	(0.048)	(0.037)
L.GDP of Primary Industries	0.000011	-0.00023	0.0039	0.00079
	(0.00020)	(0.00038)	(0.010)	(0.0057)
L.Government Revenue	0.00040	-0.00015	0.013	0.011
	(0.00078)	(0.00032)	(0.014)	(0.0085)
L.Number of Large Companies	-0.00024	-0.00025	-0.042***	-0.036**
	(0.00042)	(0.00028)	(0.0100)	(0.014)
L.Number of High School Students	-0.000055	-0.000019	-0.013	-0.0066
	(0.00022)	(0.00024)	(0.012)	(0.0078)
N	2,345	2,345	7,765	7,765

Notes: 1. All explanatory variables are standardized.
2. All four regressions control for individual grid and year fixed effects.
3. Standard errors in parentheses.
4. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

2.6 Discussions

Our cross-section and panel data analysis indicated interesting results regarding pollution and the placement of air quality monitors. While initially, central monitors were placed in polluted areas, these areas seem to have been cleaned up over time. However, it is difficult to know whether the reduction is actual reduction due to abatement technologies/change in behavior or just a shift of pollution from monitored areas to unmonitored areas.

It will be exciting to see if local governments clean up areas around local monitors as well. While local officials have an incentive to clean areas around central monitors for environmental performance evaluation, there is a lack of incentive to do the same around local monitors.

Another critical area of interest is if local governments move local monitors to show a more favorable pollution level in the province. According to table 11, we see many local pollution monitors entering and exiting the grid. It is very well possible that these monitors are moved from the current location to a favorable location nearby. Due to the limitation of our data, we cannot observe this behavior and hence cannot account for this behavior.

Appendices

Appendix A. Chapter 1 Supplementary Tables and Figures

Table A.1 Definitions of Variables in the China Meteorological Forcing Dataset

Variables	Unit	Physical meaning
Temperature	K	Instantaneous near surface (2m) air temperature.
Pressure	Pa	Instantaneous near surface (2m) air pressure.
Humidity	kg kg-1	Instantaneous near surface (2m) air specific humidity.
Wind Speed	m s-1	Instantaneous near surface (10m) wind speed.
Downward Shortwave Radiation	W m-2	3-hourly mean (from -1.5hr to +1.5hr) surface downward shortwave radiation.
Downward Longwave Radiation	W m-2	3-hourly mean (from -1.5hr to +1.5hr) surface downward longwave radiation.
Precipitation Rate	mm hr-1	3-hourly mean (from -3.0hr to +0.0hr) precipitation rate.

Table A.2 Summary Statistics for Weather Variables at Grid Level

	N	Mean (S.D.)
Temperature	33,380	0.01 (0.00)
Pressure	33,380	83683.60 (15470.12)
Humidity	33,380	178.77 (30.32)
Wind Speed	33,380	2.46 (0.94)
Downward Shortwave Radiation	33,380	280.03 (8.07)
Downward Longwave Radiation	33,380	286.45 (50.63)
Precipitation Rate	33,380	0.07 (0.06)

Note: Standard deviations are in the parenthesis after the mean of the variables.

Table A.3 Number of Local Politicians by Position

Position	Number of Politicians
China Communist Party (CPC) Secretary	222
CPC Deputy Secretary	336
Governor/Mayor	107
Vice Governor/Mayor	380
Secretary General	27
Provincial Party Committee Member	721
Total	1,072

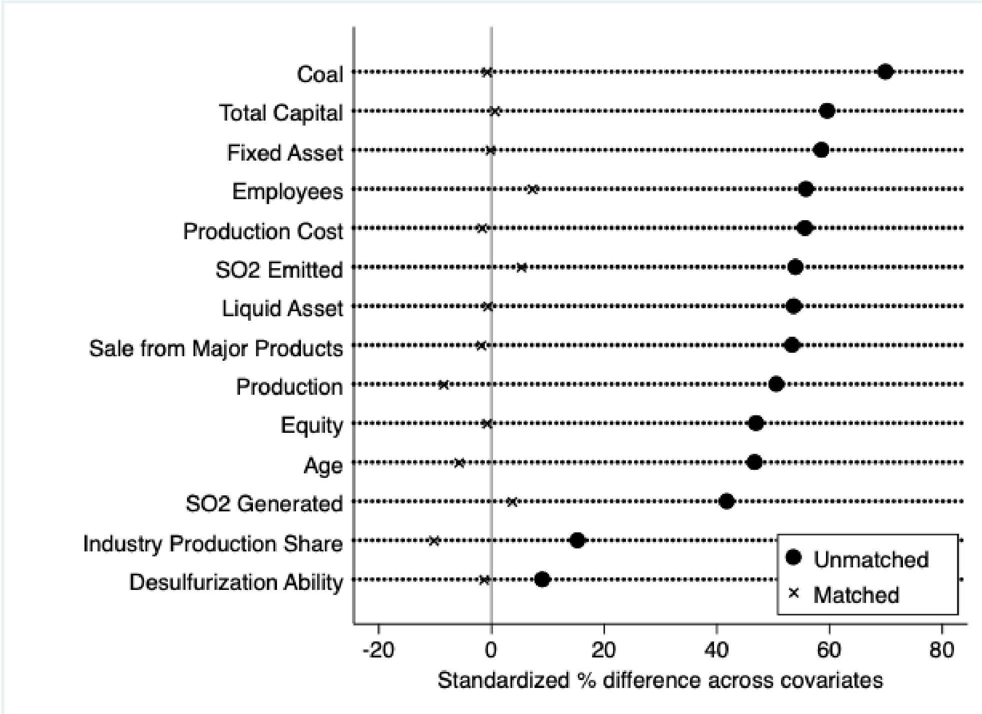

Figure A.1 Balanced of Covariates Before and After Kernel Matching

Table A.4 Balance of Covariates Before and After Kernel Propensity Score Matching

Variable	Un/Matched	Treated	Control	%Bias
Production (1,000 yuan)	U	2.2e+06	3.2e+05	50.5***
	M	1.4e+06	1.8e+06	-8.6
SO_2 Generated(ton)	U	11857	1439.9	41.7 ***
	M	8594.2	7705.3	3.6
SO_2 Emitted (ton)	U	7530.9	1146.8	53.9***
	M	6691.6	6077.2	5.2
Desulfurization Ability (kg hr-1)	U	1709.6	377.94	9.0**
	M	978.29	1187.2	-1.4
Coal (ton)	U	7.7e+05	1.1e+05	69.9 ***
	M	6.8e+05	6.9e+05	-0.9
Total Capital (1,000 yuan)	U	3.2e+06	4.6e+05	59.6***
	M	2.2e+06	2.2e+06	0.5***
Production Cost (1,000 yuan)	U	2.1e+06	2.7e+05	55.6***
	M	1.3e+06	1.4e+06	-1.8
Sales from Major Products (1,000 yuan)	U	2.5e+06	3.4e+05	53.3***
	M	1.6e+06	1.6e+06	-1.9
Age (year)	U	20.986	12.769	46.7***
	M	20.274	21.306	-5.9
Equity (1,000 yuan)	U	1.3e+06	1.9e+05	46.9***
	M	8.4e+05	8.6e+05	-0.9
Industry Production Share (percent)	U	.77823	.46645	15.3***
	M	.62568	.83683	-10.3*
Employee (person)	U	5118.2	982.67	55.8***
	M	3843.8	3315	7.1
Liquid Asset (1,000 yuan)	U	1.1e+06	2.0e+05	53.6***
	M	7.2e+05	7.4e+05	-0.8
Fixed Asset (1,000 yuan)	U	1.8e+06	2.2e+05	58.6***
	M	1.3e+06	1.3e+06	-0.3

Table A.5 Firm Event Study Result

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	SO_2 Generation (ton)	SO_2 Reduction (ton)	SO_2 Emission (ton)	Coal (ton)	Production (1,000 yuan)	Production Share (percent)	Coal Intensity	Employee (person)	FGD Ability (kg hr-1)
Treated ×2002	-286.0	-263.8	-18.2	16207.9	341040.1	0.010	0.046	17.4	-937.4
	(328.4)	(257.6)	(170.4)	(12225.7)	(212461.6)	(0.11)	(0.98)	(83.0)	(696.6)
Treated ×2003	-221.3	-698.0***	472.8***	51944.9***	275609.0	0.18	0.34	68.2	-207.1
	(327.1)	(256.6)	(169.3)	(12152.2)	(210866.3)	(0.11)	(0.97)	(82.5)	(694.1)
Treated ×2004	-235.6	-1108.4***	865.4***	55116.5***	684577.3***	0.50***	0.024	-47.5	-141.7
	(314.3)	(246.6)	(162.1)	(11646.9)	(201776.4)	(0.11)	(0.93)	(80.0)	(667.3)
Treated ×2005	-1204.2***	-1560.2***	358.6**	29637.7**	819812.8***	0.30***	0.93	-162.8**	-1405.4**
	(318.7)	(250.1)	(164.4)	(11810.6)	(204700.2)	(0.11)	(0.95)	(80.4)	(676.7)
Treated ×2006	-708.2*	-1662.6***	817.2***	129520.0***	799845.5***	0.18	0.47	-222.3***	-261.0
	(395.5)	(310.3)	(179.4)	(13133.3)	(217898.5)	(0.12)	(1.05)	(80.9)	(866.0)
Treated ×2007	-1059.1***	-1904.8***	805.7***	150623.0***	138703.7	-0.074	1.15	-137.2*	911.0
	(404.8)	(317.6)	(179.9)	(13196.0)	(219289.9)	(0.12)	(1.05)	(81.4)	(873.8)
Treated ×2008	-258.3	-922.5**	695.1***	149549.2***	1391588.4***	0.49***	0.44	-367.8***	1253.4
	(475.1)	(372.8)	(200.9)	(14924.0)	(243062.7)	(0.13)	(1.18)	(89.6)	(1024.1)
Treated ×2009	-688.5	-1268.3***	575.7***	163163.3***	764786.3***	0.12	0.34	-490.9***	1750.9*
	(428.9)	(336.5)	(190.3)	(14171.7)	(232668.9)	(0.13)	(1.13)	(87.9)	(915.5)
Treated ×2010	671.7	-31.4	638.1***	223004.6***	724792.3***	0.17	0.20	-129.6	818.7
	(423.4)	(332.2)	(186.5)	(13813.1)	(226770.2)	(0.12)	(1.10)	(86.4)	(904.8)
N	27,048	27,048	35,009	33,702	36,672	36,672	33,264	42,736	26,219

Notes: 1.The nine analyses all control for establishment, industry, and year fixed effect.
2.Coefficients for variable "Treated" and "Treated × 2001" are omitted.
3.Standard errors in parentheses.* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.6 Firm Event Study Result for Growth Rates

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Log SO_2 Generation	Log SO_2 Reduction	Log SO_2 Emission	Log Coal	Log Production	Log Production Share	Log Coal Intensity	Log Employee	Log FGD Ability
Treated ×2002	0.16***	0.12	0.22***	0.18***	0.043	0.097**	0.072	-0.0049	-0.34**
	(0.053)	(0.10)	(0.055)	(0.041)	(0.041)	(0.042)	(0.048)	(0.018)	(0.14)
Treated ×2003	0.016	0.029	0.087	0.061	0.036	0.097**	0.036	-0.018	-0.25*
	(0.053)	(0.10)	(0.055)	(0.040)	(0.041)	(0.041)	(0.047)	(0.018)	(0.14)
Treated ×2004	0.12**	0.029	0.16***	0.12***	0.16***	0.22***	-0.033	-0.040**	-0.33**
	(0.051)	(0.099)	(0.052)	(0.039)	(0.039)	(0.040)	(0.045)	(0.017)	(0.13)
Treated ×2005	0.11**	0.077	0.13**	0.17***	0.071*	0.036	0.039	-0.043**	-0.43***
	(0.051)	(0.100)	(0.053)	(0.039)	(0.039)	(0.040)	(0.046)	(0.017)	(0.13)
Treated ×2006	0.20***	-0.12	0.11*	0.24***	0.021	0.018	0.20***	-0.090***	-0.40***
	(0.063)	(0.11)	(0.057)	(0.042)	(0.042)	(0.043)	(0.049)	(0.017)	(0.14)
Treated ×2007	0.11	-0.22**	0.19***	0.19***	0.0028	-0.026	0.15***	-0.074***	-0.30**
	(0.064)	(0.11)	(0.057)	(0.043)	(0.042)	(0.043)	(0.050)	(0.017)	(0.14)
Treated ×2008	0.15**	0.046	0.19***	0.14***	0.10**	0.12***	0.024	-0.086***	-0.30*
	(0.075)	(0.12)	(0.064)	(0.048)	(0.046)	(0.047)	(0.055)	(0.019)	(0.16)
Treated ×2009	0.19***	0.10	0.24***	0.24***	0.063	0.19***	0.11**	-0.097***	-0.19
	(0.069)	(0.12)	(0.061)	(0.046)	(0.044)	(0.045)	(0.053)	(0.019)	(0.15)
Treated ×2010	0.28***	0.11	0.36***	0.25***	0.052	0.15***	0.14***	-0.055***	-0.25*
	(0.068)	(0.11)	(0.060)	(0.045)	(0.043)	(0.044)	(0.052)	(0.018)	(0.15)
N	24,871	13,901	32,815	29,803	36,260	36,260	29,499	42,676	10,803

Notes: 1.The nine analyses all control for establishment, industry, and year fixed effect.
2.Coefficients for variable "Treated" and "Treated × 2001" are omitted.
3.Standard errors in parentheses.* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.7 Grid Event Study Result

	(1)	(2)	(3)	(4)
Dependent Variable	SO_2		$\log(SO_2)$	
Sample	All	Matched	All	Matched
Treated × 2001	-8.72***	-10.5***	-0.40***	-0.44***
	(0.25)	(0.29)	(0.010)	(0.012)
Treated × 2002	-8.58***	-10.4***	-0.37***	-0.42***
	(0.24)	(0.27)	(0.0095)	(0.011)
Treated × 2003	-5.43***	-7.23***	-0.24***	-0.29***
	(0.23)	(0.25)	(0.0092)	(0.010)
Treated × 2004	-2.85***	-4.88***	-0.11***	-0.16***
	(0.22)	(0.24)	(0.0089)	(0.0097)
Treated × 2005	-0.73***	-2.74***	-0.037***	-0.096***
	(0.22)	(0.23)	(0.0088)	(0.0095)
Treated × 2006	2.09***	0.16	0.082***	0.021**
	(0.22)	(0.24)	(0.0090)	(0.0098)
Treated × 2007	2.90***	0.71***	0.14***	0.067***
	(0.22)	(0.24)	(0.0089)	(0.0097)
Treated × 2008	5.99***	3.95***	0.20***	0.13***
	(0.21)	(0.25)	(0.0085)	(0.0099)
Treated × 2009	7.64***	5.57***	0.25***	0.17***
	(0.21)	(0.25)	(0.0085)	(0.0100)
Treated × 2010	3.96***	0.82***	0.17***	0.063***
	(0.22)	(0.25)	(0.0087)	(0.010)
Observations	10,138	7,824	10,138	7,824

Notes: 1. Controls in the analysis including grid level economic factors and weather characteristics.
2. All models include grid and year fixed effect.
3. Standard errors in parentheses.
4. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

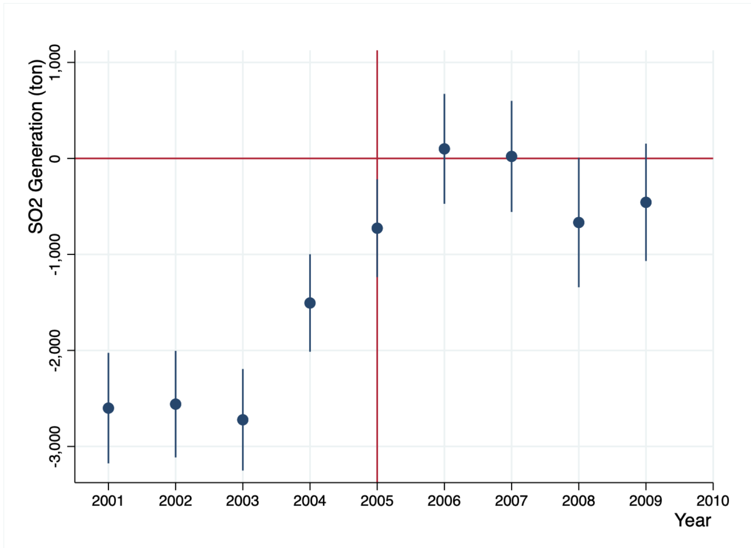

Figure A.2 Event Study on SO_2 Generation at Establishment Level

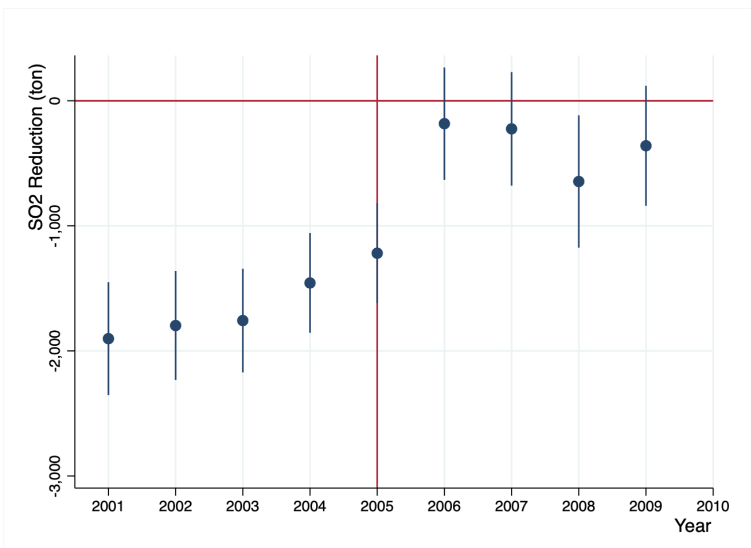

Figure A.3 Event Study on SO_2 Reduction at Establishment Level

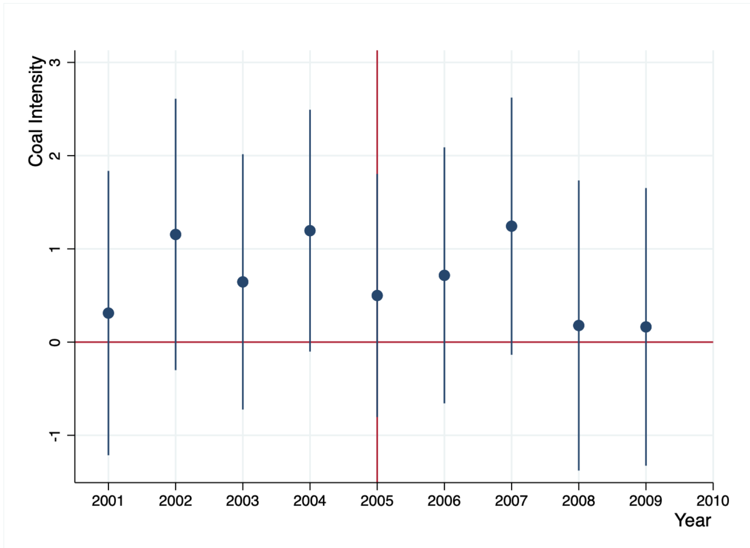

Figure A.4 Event Study on Coal Intensity Trend at Establishment Level

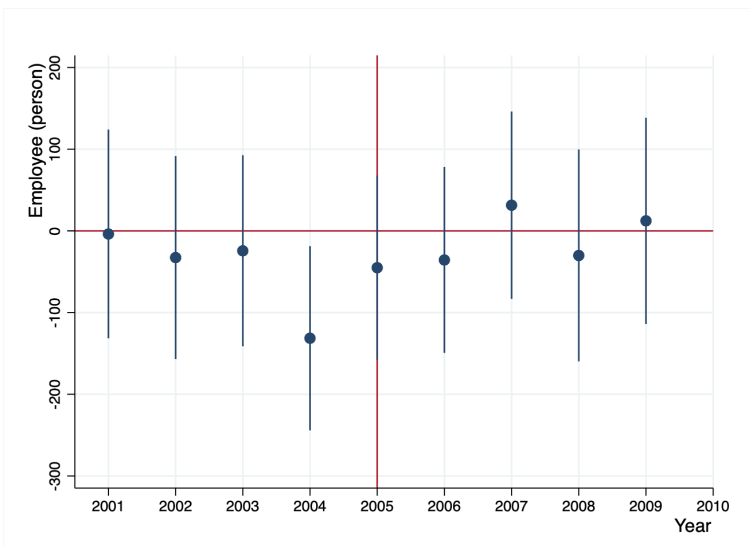

Figure A.5 Event Study on Number of Employees Trend at Establishment Level

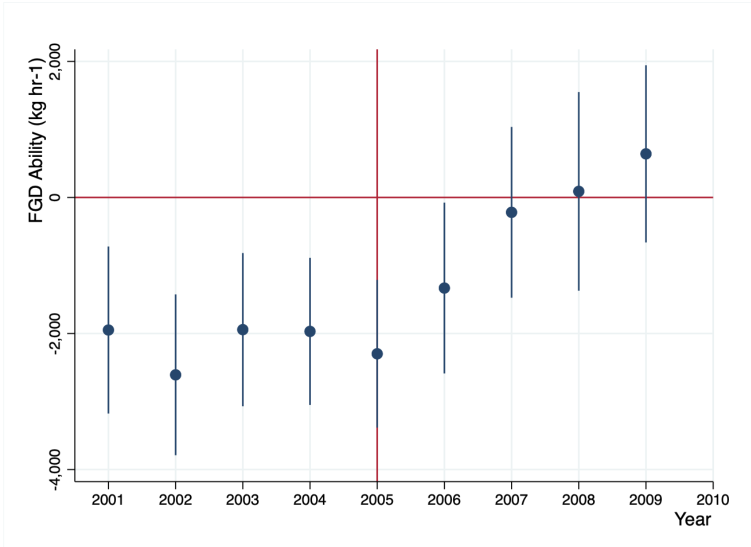

Figure A.6 Event Study on FGD Ability Trend at Establishment Level

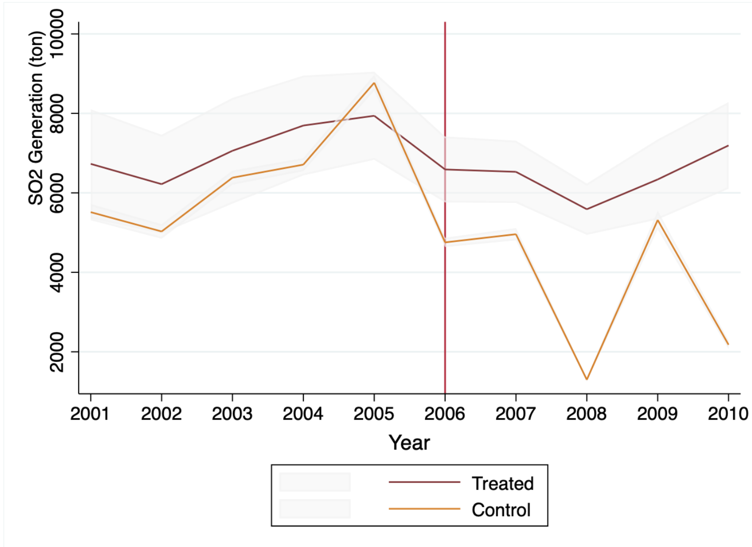

Figure A.7 SO_2 Generation Trend for Treated and Control Establishments

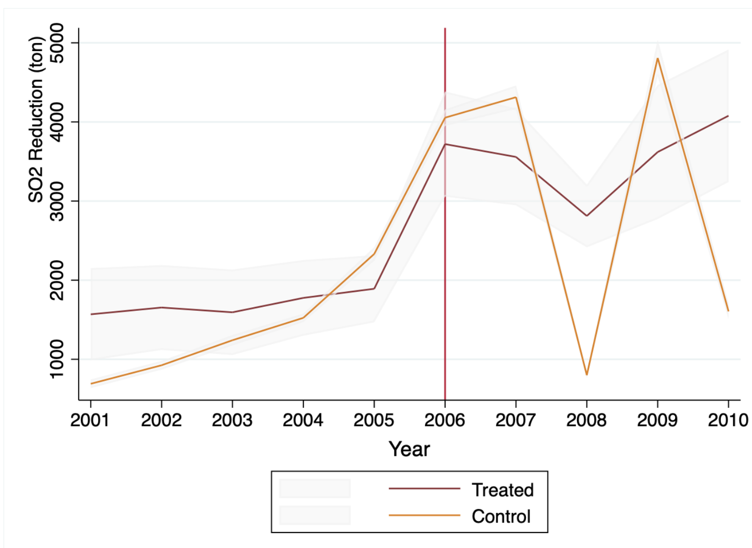

Figure A.8 SO_2 Reduction Trend for Treated and Control Establishments

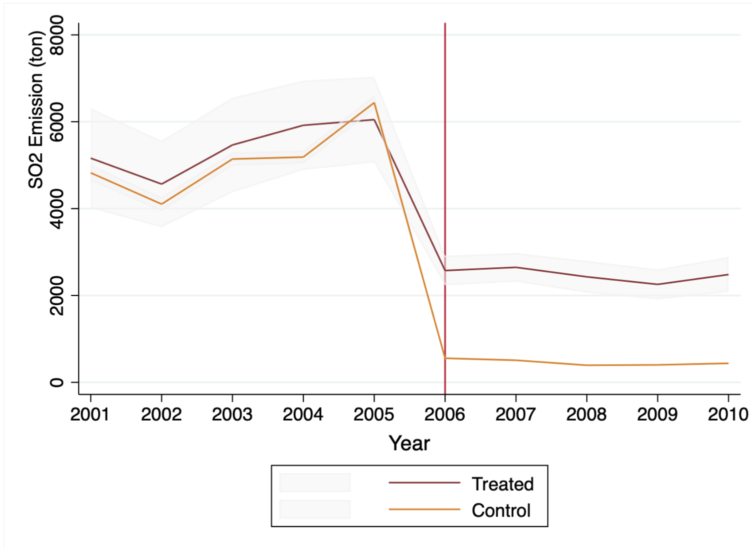

Figure A.9 SO_2 Emission Trend for Treated and Control Establishments

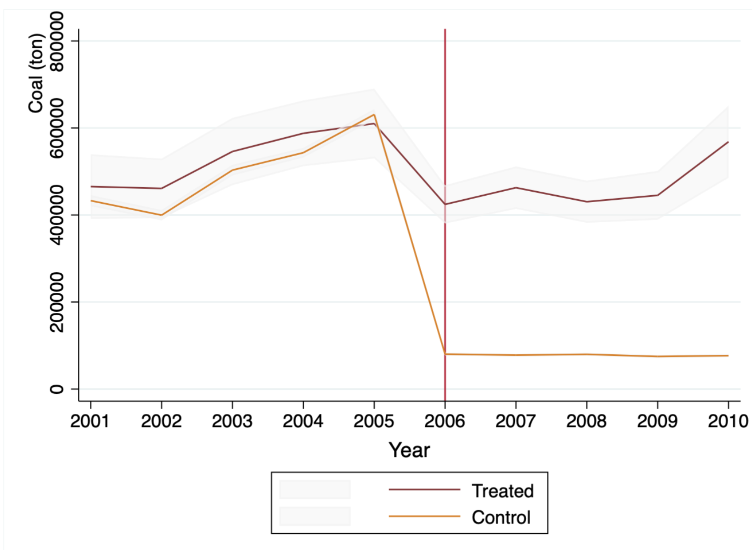

Figure A.10 Coal Usage Trend for Treated and Control Establishments

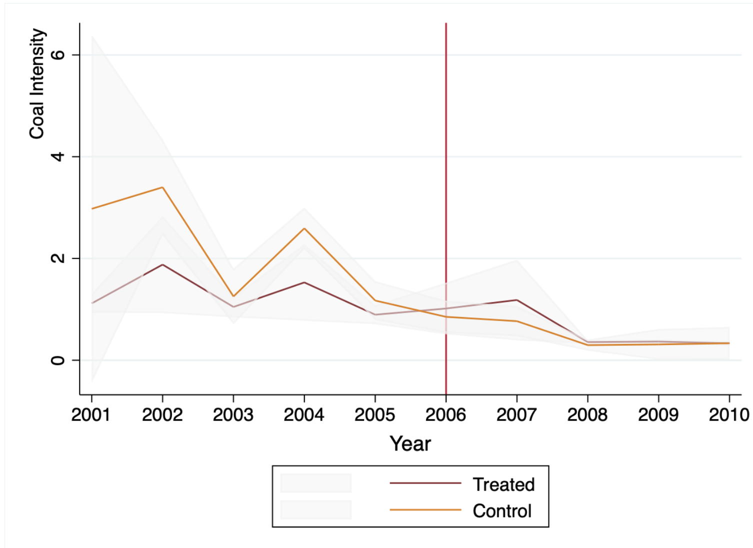

Figure A.11 Coal Intensity Trend for Treated and Control Establishments

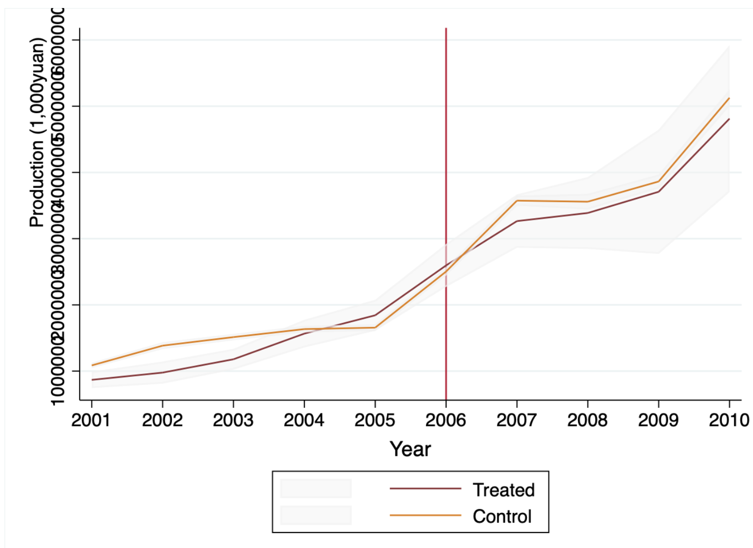

Figure A.12 Production Trend for Treated and Control Establishments

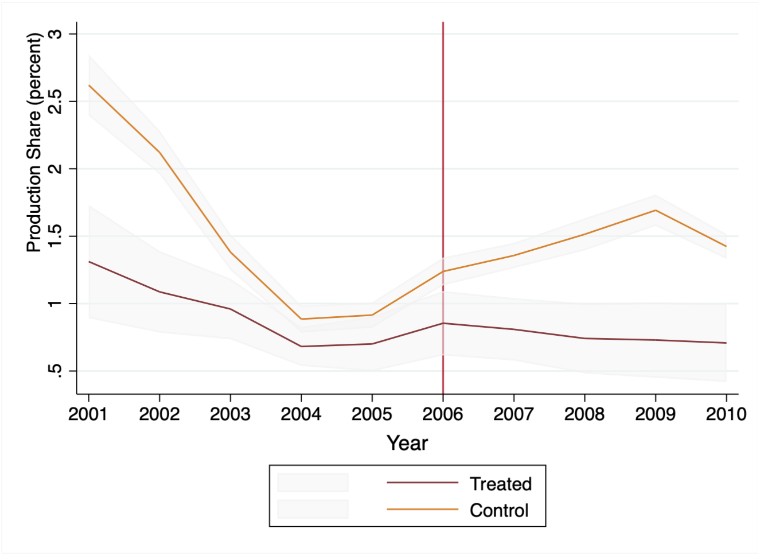

Figure A.13 Production Share Trend for Treated and Control Establishments

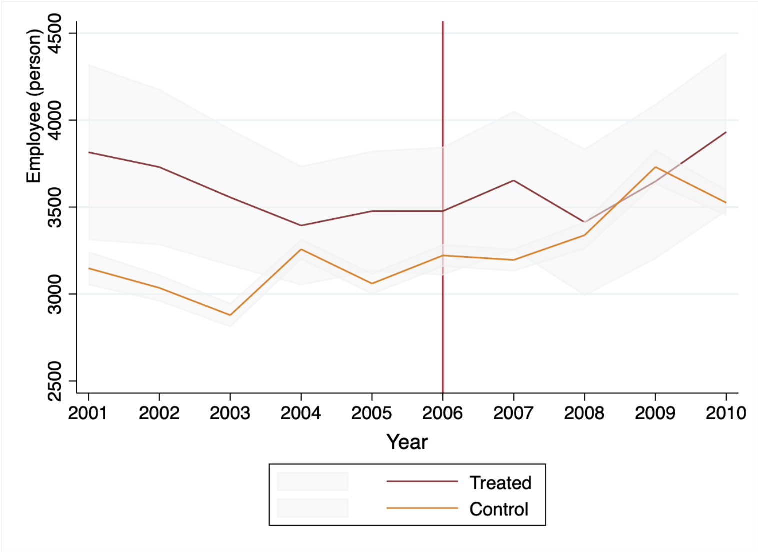

Figure A.14 Number of Employees Trend for Treated and Control Establishments

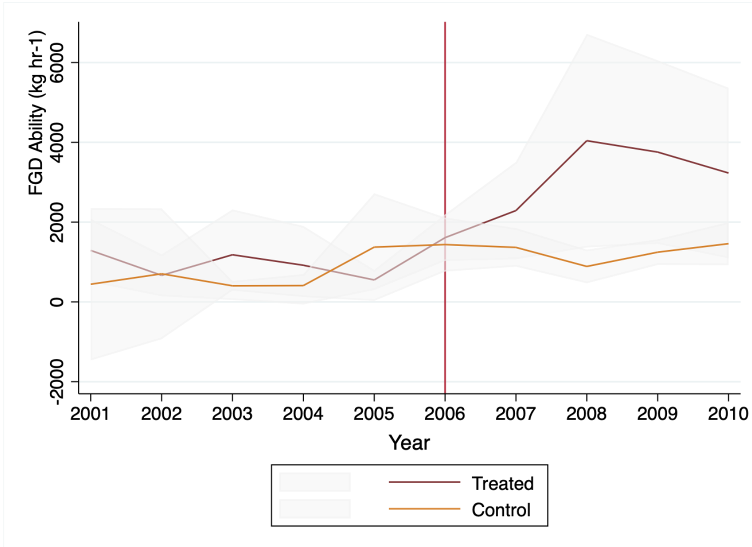

Figure A.15 FGD Ability Trend for Treated and Control Establishments

Appendix B. Chapter 2 Supplementary Tables and Figures

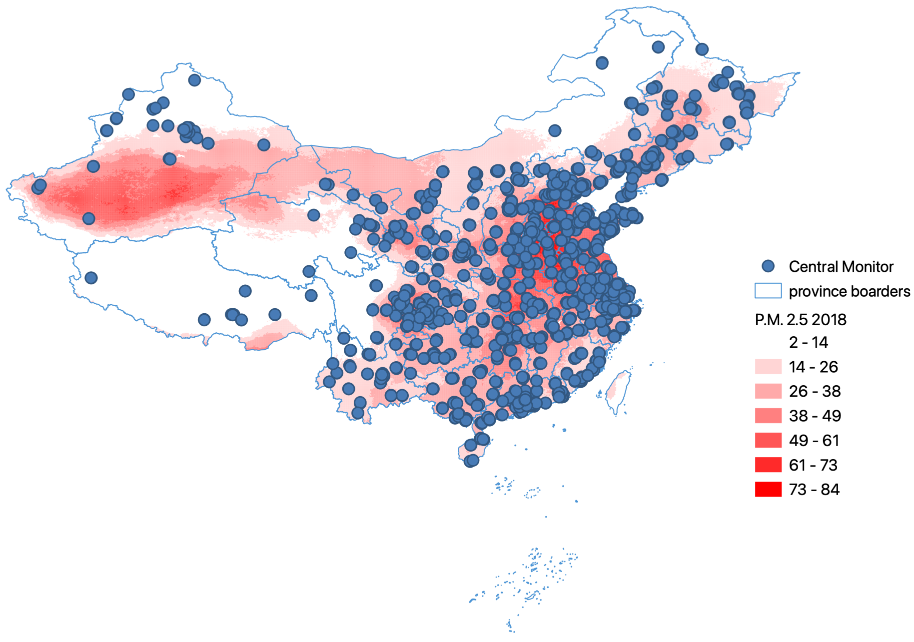

Figure B.1 P.M. 2.5 and Central Monitor Locations (2021)

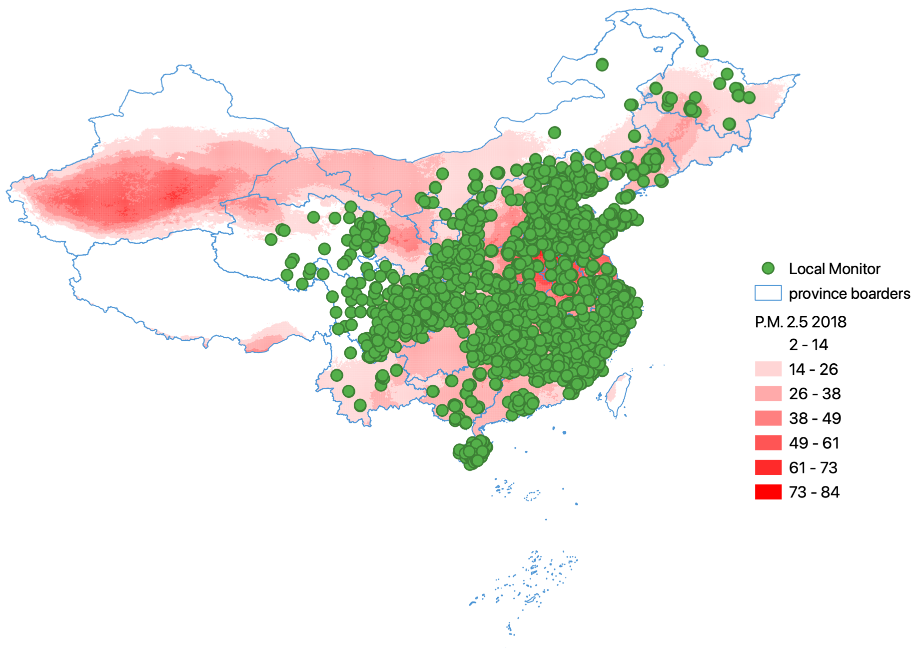

Figure B.2 P.M. 2.5 and Local Monitor Locations (2021)

Table B.1 Marginal Effects for Monitor Location in 2021 Using Linear Probability Models

	(1) Central Monitor	(2) Local Monitor
Average P.M. 2.5	-0.0019***	0.0031
	(0.00034)	(0.00067)
Length of Highway	0.0062***	0.013***
	(0.00068)	(0.00098)
Population Density	0.0037**	-0.010***
	(0.0015)	(0.0015)
Number of Schools	0.0041***	0.0057***
	(0.0014)	(0.0020)
Number of Hospitals	0.022***	0.044***
	(0.0014)	(0.0023)
Distance to the Nearest Central Monitor	-0.0014***	0.00043
	(0.00033)	(0.00059)
Distance to the Nearest Local Monitor	-0.00078**	-0.0021***
	(0.00036)	(0.00067)
GDP	-0.0067*	-0.014***
	(0.0034)	(0.0048)
GDP of Primary industries	0.0042*	0.0012
	(0.0024)	(0.0024)
Government Revenue	-0.0015	0.0020
	(0.0018)	(0.0025)
Number of Large Companies	0.0091***	0.011***
	(0.0019)	(0.0037)
Number of High School Students	-0.0026	0.0010
	(0.0017)	(0.0023)
N	338,067	212,123

Notes: 1. All explanatory variables are standardized.
2. Standard errors in parentheses.
3. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table B.2 Marginal Effects for Monitor Entry Using Linear Probability Models

	(1)	(2)
	Central Monitor	Local Monitor
L.P.M. 2.5	0.00022	0.000062
	(0.00019)	(0.00060)
L.Length of Highway	-0.00041**	0.00076*
	(0.00018)	(0.00045)
L.Population Density	0.054***	-0.0077
	(0.017)	(0.033)
L.Distance to the Nearest Central Monitor	0.0011***	0.000036
	(0.00025)	(0.00021)
L.Distance to the Nearest Local Monitor	0.00035***	0.00037**
	(0.00013)	(0.00015)
L.GDP	-0.0057	-0.00073
	(0.0047)	(0.0091)
L.GDP of Primary industries	0.0031*	0.0031
	(0.0016)	(0.0043)
L.Government Revenue	0.0032	0.0023
	(0.0021)	(0.0030)
L.Number of Large Companies	-0.00066***	-0.0016
	(0.00014)	(0.0015)
L.Number of High School Students	-0.00028	-0.0021
	(0.0020)	(0.0043)
N	1,690,335	1,060,615

Notes: 1. All explanatory variables are standardized.
2. Standard errors in parentheses.
3. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

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