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The Beneficial Impacts of COVID-19 Lockdowns on Air Pollution: Evidence from Vietnam

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Abstract

Little evidence currently exists on the effects of COVID-19 lockdowns on air quality in low-income countries, where most air pollution-linked deaths occur. We offer the first study on the lockdown impacts in Vietnam, a poorer country with worsening air pollution that has had a successful fight against early waves of the pandemic. We compile a new, rich database from various sources including satellite air pollution data for the past year from January 2020 to January 2021 that covers both the pre-pandemic and post-pandemic lockdown periods. Employing the Regression Discontinuity Design method, we find NO_2 concentration to decrease by 24 to 32 percent two weeks after the COVID-19 lockdown. While these positive effects on air quality are comparable to those found in previous studies on stricter gasoline regulations or transition to cleaner energy sources, they dissipate after ten weeks. Our findings are robust to different measures of air quality and model specifications. We also find that mobility restrictions are a potential channel for improved air quality. Finally, our back-of-the-envelope calculations suggest that two weeks after the lockdown, the economic gains from better air quality are at least $33.9 million US dollars.

JEL Classification: D00, H00, O13, Q50

Key words: COVID-19, air pollution, mobility restriction, RDD, Vietnam

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1. Introduction

The COVID-19 pandemic has now been recognized as a global health catastrophe that resulted in more than 5.4 million deaths worldwide by December 2021. Countries all over the world have implemented a wide range of policy responses such as stay-at-home orders, social distancing, and closure of retail establishments and non-essential businesses to slow down the pandemic infection. There is a growing body of literature on the negative economic consequences of the pandemic on household behaviors, consumption, and employment outcomes,[1] but only a handful of studies have examined the impacts of COVID-19-induced lockdowns on air quality.

Air pollution poses major challenges to human health including heart and lung damage and other diseases (Liu et al., 2019), and it is estimated to cause more than 4.6 million annual deaths worldwide (Cohen et al., 2017). Notably, human industrial and traffic activities represent a significant contribution to reduced air quality (World Bank, 2016) and most recorded air pollution-linked deaths occur in developing countries, where environment protection laws regarding these activities are weak or do not even exist. Yet, very few studies currently exist that provide in-depth examination of the impacts of these activities on air quality in a low-income country context.

We make several new contributions to the literature on the impacts of COVID-19. First, we investigate the effects of COVID-19 induced lockdown on air quality in Vietnam—a poorer country. Indeed, Vietnam offers an interesting, and perhaps even unique, case study for various reasons. The country has been struggling with alarming air pollution that has been steadily rising with its solid economic growth. Annual economic losses associated with air pollution are estimated to cost Vietnam around $24 billion USD, or 5.2 percent of the country's Gross Domestic Product (GDP) (World Bank, 2016). Figure 1 shows that Vietnam's concentration of $PM_{2.5}$ (fine particulate matter) is above the global average for the past 20 years. It is comparable to that of China—a country widely recognized as having high air pollution but with an income level about thrice that of Vietnam—and below countries currently with the most polluted air levels such as Bangladesh and India.

At the same time, Vietnam won international praise for its successful fight against early waves of the COVID-19 pandemic with relatively few cases of infection and death. Furthermore, the country still managed to achieve an impressive GDP growth rate of 2.8 percent in 2020, ranking it among the fastest-growing economies in the world (Morisset & Madani, 2020). The Vietnamese government imposed a nationwide lockdown during April 1-14, 2020, which entailed tough controls on mobility and cessation of economic activities. This setting provides a rare natural experiment to investigate whether the lockdown helps reduce the existing air pollution levels. To our knowledge, we offer the first study to examine the impacts of the COVID-19 lockdown on air quality for Vietnam.

Second, regarding the data and analytical front, we apply a rigorous econometric technique on a new and rich database that we assemble from various reliable sources covering the country both in the pre-pandemic and post-pandemic periods in the past year (i.e., January 1, 2020 to January 10, 2021). A major challenge to estimating the causal impacts of COVID-19 on air quality is endogeneity issues since unobserved factors can simultaneously affect lockdown policies and air quality. For example, low-income countries likely have implemented less stringent policies during the pandemic and may also have weaker environment protection programs in place. We overcome these issues by using the Regression Discontinuity Design (RDD) approach, a quasi-experimental econometric technique that allows us to compare the impacts of the lockdown on air quality in a time window around the lockdown date.[2]

We obtain daily, district-level satellite data on air pollution from the European Union's Copernicus programme. Our paper departs from the station-based data often used in previous studies, which are likely not random and do not provide representative data on an area's air quality. We also analyze a variety of other real-time data sources including daily weather data, real-time human mobility data, government responses to COVID-19, and other sub-national characteristics.

Our findings suggest that the lockdown imposed to combat COVID-19 improves air quality in Vietnam. Specifically, we find the average concentration of NO_2 to drop by 24-32 percent two weeks after the lockdown date. These positive effects are comparable to those found in previous studies on gasoline regulations and transition to cleaner energy, but they fade away in about ten weeks. Further analysis of the heterogeneous effects of lockdown policies shows that the positive impacts are stronger in areas without coal-fired stations and cement plants. We also find the lockdown to be associated with less mobility in different categories, except for residential mobility. Our findings remain consisent when we analyze a subsample of areas under the second lockdown in Vietnam and are robust to various placebo and robustness analysis including different time bandwidths, functional forms, estimation methods, falsified lockdown dates, and external validity tests using data from other countries. Lastly, some back-of-the-envelope calculations provide tentative evidence that two weeks after the lockdown, the economic gains from better air quality are at least $33.9 million US dollars.

This paper consists of six sections. We next review recent studies on COVID-19 and air pollution (Section 2.1), present an overview of air pollution in Vietnam (Section 2.2), and briefly discuss the nationwide lockdown (Section 2.3). We subsequently describe our newly constructed database in Section 3 before discussing the empirical model in Section 4. In Section 5, we present the main findings (Section 5.1) together with robustness checks, heterogeneity analysis, and further extensions (Section 5.2), discuss the potential channels for improving air quality (Section 5.3), and offer some back-of-the-envelope cost-benefit analysis (Section 5.4). We finally conclude in Section 6.

2. Brief Literature Review and Air Pollution in Vietnam

2.1. Brief Literature Review

Several studies investigate changes in global air quality during the pandemic. Using an input-output model for 38 regions around the word, Lenzen et al. (2020) find the pandemic to reduce global greenhouse gas, $PM_{2.5}$, and air pollutants by 4.6 percent, 3.8 percent and 2.9 percent respectively. Venter et al. (2020) analyze station-based air quality data in 34 countries and find concentration of NO_2 and $PM_{2.5}$ to decrease by 60 percent and 31 percent respectively during the pandemic. Most recently, studying satellite data for 164 countries, Dang and Trinh (2021) find the global concentration of NO_2 and $PM_{2.5}$ to decrease by 5 percent and 4 percent after the global lockdowns.

However, studies focusing on specific countries (that are richer than Vietnam) offer mixed evidence. In particular, He, Pan, and Tanaka (2020) show that city lockdowns led to considerably improved air quality in Hubei, the province at the center of the outbreak, as measured by Air Quality Index (AQI) and $PM_{2.5}$. But except for NO_2, Almond, Du, and Zhang (2020) find ambiguous pandemic impacts and perhaps even more pollution near Hubei. Outside China, Brodeur, Cook, and Wright (2021) find the lockdown to result in reduced $PM_{2.5}$ emissions in the United States. Yet, Chang, Meyerhoefer, and Yang (2021) find air poluttion to increase 5-12 percent in two largest cities in Taiwan.

2.2. Air Pollution in Vietnam

Air pollution has recently worsened alongside Vietnam's steady economic growth, as earlier discussed with Figure 1. The country also ranked as the fifth highest emitter of black carbon in the world during 2000–2008 (Kurokawa et al., 2013). Its industrial production and power generation can be major sources of air pollution, with coal-fired power contributing to 4,300 premature deaths in 2011 (Koplitz et al., 2017). Still, coal-fired power currently takes the lion's share (i.e., more than 40 percent) of the country's total generated power (Baker, 2018). Vietnam expects to build 26 additional coal power stations after 2020, despite its plans to generate more electricity from renewable sources (Bich Ngoc, 2018). For illustrative purpose, Figure A1 (Supplementary Material) shows NO_2 concentration across districts in Vietnam in 2019, as well as the distribution of coal-fired power stations and cements plants. These plants are mostly located in northern Vietnam, which may possibly contribute to more air pollution in this region than in southern Vietnam (Nguyen Quy, 2020).

Another main source of air pollution is transportation. By 2020, Vietnam had approximately 3.6 million automobiles and 58 million motorbikes, which are mostly concentrated in large cities (Do, 2020). Many of them are old vehicles with limited emission control technology, which generate a large amount of air pollutants. Nguyen and Kajita (2018) find that dust concentration in the air at traffic junctions in big cities is 3 to 5 times higher than permitted standards, while the corresponding figures for daily average concentration of CO and NO_2 are 1.2 to 1.5 times higher in some large intersections. Analyzing an online survey on air pollution sources, Nguyen and Blume (2017) show that respondents are most concerned about transportation (83 percent), to be followed by industrial production (79 percent), and power generation (71 percent).

There is a small but growing literature on the negative effects of air quality on human health in Vietnam. Examining two largest hospitals in Ho Chi Minh City, Phung et al. (2016) observe an increase in respiratory admissions of between 0.7 percent to 8 percent for a 10-$\mu g/m^3$ increase of each of the pollutants PM_{10}, NO_2, and SO_2. Vu et al. (2020) find that NO_2 and $PM_{2.5}$ cause 172 and 1136 deaths related to lung cancer, cardio-pulmonary and Ischemic Heart Disease (IHD) in Ho Chi Minh City. We use these studies' results to perform back-of-the-envelope calculations on the monetary benefits of improved air quality in Vietnam (Section 5.4).[3]

2.3. Nationwide Lockdown in Vietnam

Since the beginning of the COVID-19 outbreak, lockdown has been implemented as a key policy response in many countries to prevent further spread of disease. Vietnam is more vulnerable to the pandemic due to its proximity to China and its low-resource healthcare system. Responding to this urgency, after detecting the first two cases on January 22, 2020, the country declared a public health emergency on February 1, 2020. The number of cases, however, increased approximately by 15-folds from 15 cases to 206 cases during March, 15-31, 2020. Accordingly, the government imposed the first nationwide lockdown from April 1 to 15, 2020. The lockdown measures included strict stay-at-home orders (except for buying critical supplies, health emergency cases, or working at essential businesses), quarantines, and social distancing. Border controls were tightened and all commercial flights into and out of the country were banned.

Vietnam has won international praise for its early success against COVID-19 (Hartley et al., 2021; Trevisan et al., 2020). For example, the spirit of the country's fight against the pandemic can perhaps be best epitomized in the words of Prime Minister Nguyen Xuan Phuc "*Every business, every citizen, every residential area must be a fortress to prevent the epidemic*" (Pham, 2020). Protection measures such as social distancing, washing one's hands, and staying at home were portrayed as actions of patriotism, which were well received by the public (Le Thu, 2020). These measures were effective, resulting in only 59 new infected cases being confirmed during the first 14-day nationwide lockdown. Within the subsequent 99 days, the country had no community transmission despite extensive testing. Consequently, while strict COVID-19 lockdown orders had still been in effect in many regions of the world, Vietnam relaxed social distancing rules for almost all provinces and cities on April 23, 2020.

Vietnam's success in curbing the spread of COVID-19, however, comes at a cost to the economy. Despite achieving an impressive, world-leading GDP growth rate of 2.9 percent in 2020, the country's growth in this year is still less than half those of more than 6 percent in preceding years (GSO, 2021a). About 32.1 million people aged 15 and over nationwide were estimated to be negatively affected by COVID-19 through increased unemployment, fewer working hours, and income decreases (GSO, 2021b). While those that were employed or were in good health could better withstand the pandemics, the worst-hit groups were more vulnerable workers including migrant workers, workers working below the minimum wages, or those working in the informal sector (Dang, Giang, & Do, 2021; Dang & Nguyen, 2020).

3. Data

We obtain air pollution measurements in Vietnam from January 1, 2020 to January 10, 2021, provided by the Sentinel-5P/TROPOMI (S5P) instrument of the European Union's Copernicus programme. The S5P satellite uses spatial resolution of 5.5 km and provides a (near-)global coverage of air pollution caused by NO_2 and other pollutants such as O_3, SO_2, and CO. We use NO_2 as the main measure as it is the most appropriate indicator of air pollution recommended by the European Union's Copernicus programme.

Since NO_2 concentration levels in the atmosphere are highly variable and sensitive to changes in weather conditions, we collect global daily data on temperature and precipitation from the National Center for Environmental Prediction (NCEP) at the National Oceanic and Atmospheric Administration (NOAA) as control variables. We extract the weather data at the district level using a similar process as with the air pollution data.[4]

To further investigate the channels and heterogeneity of impacts, we collect data on various indicators from different sources for the country. These variables include i) locations of coal-fired stations and cement plants, ii) industrial production (including FDI and monthly nightlight data), iii) agricultural production, iv) public perceptions about the environment, v) human mobility patterns, and vi) number of flights in all the country's eight international airports. They are mostly available at the province level, except for the nighlight data at the district level. For further robustness checks, we obtain information on government response indexes from the Oxford COVID-19 Government Response Tracker (OxCGRT). This tracker was implemented by the University of Oxford's Blavatnik School of Government to systematically collect information on policy stringency taken by governments to tackle the pandemic since February 2020 (Hale et al., 2021). We provide a more detailed discussion of the various datasets and their sources in the Supplementary Online Materials.[5]

4. Empirical Model

Leveraging the abrupt discontinuities of economic activities when the lockdown goes into effect, we employ the Regression Discontinuity Design (RDD) model. The motivation of this approach is that within a relatively narrow window of time around the lockdown date, the unobserved factors influencing air quality are likely similar so that observations before the lockdown provide a counterfactual group that can be compared with observations after the lockdown. Our framework is also identifed as a Regression Discontinuity Design in Time (RDiT) approach, which has been used in studies examining changes in air quality caused by a specific event (e.g., Auffhammer & Kellogg, 2011; Dang & Trinh, 2021; Hausman & Rapson, 2018). We estimate the following reduced form equation

$$A_{it} = \delta L_{it} + f(d_{it}) + \theta X_{it} + \mu_p + \pi_t + \varepsilon_{it} \qquad (1)$$

In Equation (1), the outcome of interest (A_{it}) is changes in air quality on day *t* in district *i*. The parameter of our interest is δ, the (local average treatment) impacts of the lockdown on air pollution. The treatment variable (L_{it}) is a dummy variable that equals 1 after the lockdown and 0 otherwise. d_{it} is the running variable which represents the number of days before and after the official lockdown date. To provide robust analysis, we let the function $f(d_{it})$ take different functional forms to flexibly control for variations in air quality that would have occurred in the absence of the lockdown. They include (i) the linear model (d_{it}), (ii) the linear model with the interaction term of the running variable and the treatment variable ($L_{it}*d_{it}$), (iii) the quadratic model (d_{it}^2), and (iv) the quadratic model with the interaction term of the running variable and the treatment variable ($L_{it}*d_{it}^2$). As the lockdown in Vietnam was implemented during April 1-14, 2020, we use a bandwidth of two weeks before and after the lockdown date (April 1) as our preferred time bandwidth. But we also present results for different bandwidths to investigate the duration of the lockdown impacts.

We include in Equation (1) X_{it}, a vector of control variables that may affect air quality such as daily temperature and daily precipitation. We also include the province fixed effects (μ_p) and time fixed effects (π_t) to control for unobservable time-invariant province or time characteristics, and ε_{it} denotes the error term.[6]

Equation (1) assumes a sharp RDD model where the lockdown is strictly implemented in Vietnam. This model is consistent with the widely accepted views in both the academic literature and the media about the country's strict and successful implementation of the lockdown (Huynh, 2020; Trevisan et al., 2020). But as a robustness check for the (unlikely) case that not all business activities and travel cease exactly by the time of the lockdown, we also employ a fuzzy RDD model where the running variable measures the degrees of strictness of the lockdown implementation. We obtain these running variables (indexes) from the OxCGRT data, which range from 0 to 100, with higher scores indicating more stringent policies. As illustrated in Figure A2 (Supplementary Material), the stringency index increases significantly over time and reaches the highest value during the two-week lockdown. We create an instrument E_{it} for the lockdown variable, which equals one when the stringency (or response) index of government policies S_{it} is positive ($S_{it} > 0$), and zero otherwise. We then apply the Two-Stage Least Squares (2SLS) method to estimate the following equations

$$L_{it} = \gamma E_{it} + g(S_{it}) + \tau X_{it} + \varphi_p + \omega_t + \epsilon_{it} \quad (2)$$

$$A_{it} = \beta L_{it} + h(S_{it}) + \lambda X_{it} + \alpha_p + \vartheta_t + \nu_{it} \quad (3)$$

We employ different indexes from the OxCGRT data including (i) the stringency index, (ii) the government response index, and (iii) the containment and health index. Similar to Equation (1), we control for weather conditions as well as province and time fixed effects. The identifying assumptions for Equations (2)-(3) require that our instrument (stringency index) is correlated with the treatment variable (lockdown) and it affects the outcome (air quality) only through the treatment variable.

We discuss next some potential threats to the validity of our RDiT approach. First, the covariates should not jump around the cut-off (i.e., the official lockdown date). Our key control variables are temperature and precipitation. Following Lee and Lemieux (2010), we replace the dependent variable with each of these weather variables and reestimate Equation (1), controlling for the province and time fixed effects. Figure A3 (Supplementary Material) shows no discontinuity at the cut-off point, which rules out this concern. Second, to address potential serial correlation concerns (Hausman & Rapson, 2018), we cluster the standard errors on both the location and time dimensions. Finally, we provide several robustness checks including using the lagged dependent variable and conducting a "Donut" RDD to address potential sorting and anticipation effects (Barreca et al., 2011). We discuss the results of these tests in the Supplementary Online Materials.[7]

5. Estimation Results

5.1. Main Findings

As a first look at the impacts of the COVID-19-induced lockdown on air quality, we run a data-driven RDD regression of NO_2 concentration on the number of days around the lockdown date, using the optimal (time) bandwidth proposed by Imbens and Kalyanaraman (2012). The results, plotted in Figure 2, show that air pollution sharply descreases two weeks after the lockdown. This figure also confirms the short-lived duration of lockdown impact when economic activities return to normal.

We turn next to estimating lockdown effects on air pollution using the (sharp) RDiT model (Equation (1)) and report the estimation results in Table 1. Each of the 24 cells in this table represents the lockdown impacts estimated from a separate regression, with the bandwidth shown in the column headings and the functional form of the running variable shown in the row headings. We control for the province and time fixed effects and cluster the standard errors at the district-day level in all the regressions. Our preferred models are presented in Columns (2), (4), and (6), which control for weather conditions (i.e., temperature and precipitation). But we also present the results without these control variables in Columns (1), (3), and (5) for comparison and robustness checks.

Overall, Table 1 suggests that the COVID-19-induced lockdown has strongly statistically significant impacts on improving air quality at the 1 percent level. This result remains qualitatively similar, regardless of different sets of control variables, functional forms of the running variable, or time bandwidths around the lockdown date. We are particularly interested in the bandwidth of two weeks as this is the duration of the official lockdown in Vietnam. The results suggest that the lockdown leads to a 5.808 (mole per square kilometer - mol/km^2) decrease in NO_2 concentration (Panel A, column 2), which equals a 24-percent reduction (compared to an average value of NO_2 of 24.441 mol/km^2 before the lockdown). Using different functional forms of the running variable (Panels B to D) results in similar estimates, although the impact magnitudes are more pronounced when we account for non-linearity. For example, the estimated impacts are larger at 32 percent for the model with the quadratic interaction term (Panel D, column 2).

These estimated impacts are stronger than that of Dang and Trinh (2021) who find a 5-percent decrease in global air pollution due to the pandemic-induced lockdown, but are more similar to those in some previous country-specific studies. In particular, Almond et al. (2020) show a decrease in NO_2 concentration in Hubei and all regions in China by 43.6 percent and 31.4 percent, respectively while Berman and Ebisu (2020) find a decline of 25.5 percent of NO_2 in the United States.

Table 1 also suggests that the negative lockdown impacts on NO_2 diminish over time, or when larger bandwidths are considered. Specifically, the reduction of NO_2 hovers around 18 percent for four and eight weeks after the lockdown (Panel A, columns 4, 6). This suggests that the reduction in air pollution may be short-lived once lockdown policies are eased and economic activities return to normal. We further estimate the short-term impacts of the lockdown on air pollution by using different bandwidths and applying the parametric RDD model that includes the interactions of the running variable (linear and quadratic terms) with the lockdown variable. We plot in Figure 3 the estimated coefficient and its 95 percent confidence interval, which confirms that the lockdown impacts disappear 10 weeks after the lockdown.

Table A1 (Supplementary Material) further illuminates the lockdown effects on air pollution using alternative measures of air quality. We use three parameters that are available, including CO, SO_2, and O_3. We find some evidence of reduced levels of CO (two or four weeks after the lockdown) and SO_2 (eight weeks after the lockdown). But the estimation results are mixed for O_3, which increases over two and four weeks after the lockdown, but decreases eight weeks after the lockdown. Several studies also find ambiguous effects of lockdown policies on

O_3 (e.g., Venter et al., 2020). A possible explanation for the increase in O_3 concentration for the two-week or four-week periods after the lockdown is warmer weather during these periods.

5.2. Robustness Checks and Further Analysis

Our results are robust to a number of sensitivity checks which we discuss in more detail in the Supplementary Online Materials. These include employing different methods to calculate the optimal bandwidths, conducting various placebo tests, addressing possible sorting and anticipation effects near the lockdown dates, accounting for the (remote) possibility that the economy may not completely shut down by the time of the lockdown with a fuzzy RDD model, specifying the changes in air pollution levels in the alternative logarithmic form, and controlling for potential differential time trends at the province level.

We turn next to examining heterogeneity of impacts. For example, we explore the question whether the lockdown has differential effects on locations with and without coal-fired power stations. Since coal-fired power stations were allowed to be in normal operation during the lockdown like most other manufacturing activities (GoV, 2020), locations with these power stations might not have been affected by the lockdown and consequently might have not seen reduced air pollution.

Put differently, locations without these power stations may likely have had more reduced air pollution due to the lockdown. The estimation results, shown in Table 2, Panel A, confirm our expectation. Similarly, locations without cement plants also had more decreased air pollution, as shown by the results in Table 2, Panel B. Furthermore, locations without either coal-powered stations or cement stations had even more reduced air pollution in the two-week period after the lockdown as well as over longer periods (Table 2, Panel C).

We further extend our analysis to study a number of relevant questions: (i) Whether the less industrialized locations and agricultural production have more reduced air pollution after the lockdown?; (ii) Whether citizen perceptions about the environment affect the impacts of the COVID-19-induced lockdown on air pollution?; (iii) Does our analytical framework to estimate the impacts of the lockdowns on air quality generalize to other countries? (i.e., does our analytical framework has external validity?); and (iv) What are the impacts of the second lockdown on air quality? We discuss the results to these questions in the Supplementary Online Materials.

5.3. Potential Mechanisms for Improving Air Quality

We provide some insights on the potential mechanisms through which the COVID-19-induced lockdown could result in improved air quality. Previous studies have examined the relationship between COVID-19 and mobility restrictions, in particular the role of traffic activities in increasing air pollution, for richer countries and globally. For example, analyzing Google mobility reports (GCMR) data, Coibion, Gorodnichenko, and Weber (2020) show that lockdowns substantially deter social mobility in the United States. Dang and Trinh (2021) analyze the same database and find significant reductions of global traffic mobility during the pandemic lockdowns.

Using this same dataset, our estimation results, shown in Table 3, reaffirm these findings for Vietnam. Table 3 shows that mobility activities decline significantly after the lockdown, and the results are consistent across bandwidths (Panels A, B, and C). In particular, the lockdown results in less mobility in categories such as “essential services” (e.g., grocery and pharmacy, workplace) and “non-essential services” (retail and recreation, parks), but more mobility in the “residential” category. We note that our findings should be interpreted as short-term lockdown effects on mobility given the small window of time used in our RDiT framework.

For further comparison, we examine another source of mobility data provided by Apple. Unlike the Google mobility data, the Apple dataset provides statistics of daily changes in driving and walking direction requests from its users. The data for Vietnam are, however, only available for the country's two largest cities (i.e., Hanoi and Ho Chi Minh City); consequently, the number of data points significantly decreases to just more than 700. Therefore, we are unable to apply the RDiT model to analyze this dataset, but we use a flexible event study framework to help mitigate concerns about the common trends. Specifically, we decompose the lockdown effects (L_{it}) into coefficients up to 6 weeks prior to and following the lockdown date. Following the main analysis, we include temperature and precipitation as the control variables and the province and month fixed effects. The estimation results are qualitatively similar, indicating that driving and walking activities decrease significantly during the lockdown period (Supplementary Material, Figure A4).

Finally, we collect international and domestic inbound and outbound flight data from all the eight international airports in Vietnam and examine how the lockdown affects the number of flights. About 5,000 people who live within 20 km of airports across the world are estimated to die prematurely each year due to long-term exposure to aviation-attributable $PM_{2.5}$ and O_3 (Yim et al., 2015). As such, the lockdown that results in cessation of air transport can improve air quality and reduce health-related risks. Using the event study framework, our results show a 40-60 percent reduction in the number of daily domestic and international flights during the lockdown compared to the week prior to the lockdown (Supplementary Material, Figure A5).

5.4. Tentative Cost-Benefit Analysis

While the economic costs of enforcing pandemic-induced lockdown policies are widely considered prohibitive, these measures could unintentionally result in certain benefits coming from improved air quality. We start by estimating the health benefits of reduced air pollution, relying on two experimental health studies discussed earlier in Section 2.2 (Phung et al., 2016; Vu et al., 2020). Since data on $PM_{2.5}$ are unavailable for Vietnam, we employ the global analysis of $PM_{2.5}$ and NO_2 from Dang and Trinh (2021) and find a one-percent increase in NO_2 to be associated with a 0.59-percent increase in $PM_{2.5}$ (see Figure A6, Supplementary Material). The 28-percent reduction of NO_2 for Vietnam (Table 1) would then correspond to a 17-percent reduction of $PM_{2.5}$.

Given these estimated reductions of NO_2 and $PM_{2.5}$ and re-weighting Vu et al.'s (2020) estimates using Ho Chi Minh City's population share in the national total population, we find that two weeks after the lockdown, the number of deaths attributable to NO_2 and $PM_{2.5}$ are lowered by 20 and 79 respectively (Table 4, Panel A).[8]

Regarding hospital admissions of pollution-related diseases, Phung et al. (2016) estimate that a one-percent decrease in concentration of NO_2 leads to 0.15 percent and 0.07 percent decreases in hospital admissions of respiratory and cardiovascular diseases, respectively.[9] These figures translate to 4.2 and 1.96 percent decreases of respiratory and cardiovascular admissions for the two-week period after the lockdown. Again, re-weighting the daily average number of hospital admissions from Phung et al. (2016) (23 and 31 for respiratory and cardiovascular, respectively) against the national population, we find the total numbers of hospital admissions to decrease by 234 for both diseases (Panel A, Table 4).

We provide next some rough cost-benefit analysis of reduced air pollution from the lockdown. We estimate the monetary benefits of better air quality using the value of statistical life (VSL) approach, which is an aggregate measure of people's willingness to pay (WTP) to reduce fatality risks. This approach is widely used to measure the trade-off rate between fatality risk and money (Kniesner & Viscusi, 2019) and most recently in the context of COVID-19 (Alvarez, Argente, & Lippi, 2021; Hall, Jones, & Klenow, 2020). In particular, using a formula suggested in World Bank (2016), Bui et al. (2021) calculate the VSL for Vietnam as follows

$$VSL_{VNM,2011} = VSL_{OECD,2011} \times \left(\frac{Y_{VNM,2011}}{Y_{OECD,2011}}\right)^{e} \quad (4)$$

where $VSL_{VNM,2011}$ is the VSL of Vietnam in 2011 (in million US dollars), while $VSL_{OECD,2011}$ is the average base VSL estimate from a sample of OECD countries in the same year. $Y_{VNM,2011}$ and $Y_{OECD,2011}$ are the GDP per capita for Vietnam and OECD countries in 2011, respectively; e is the income elasticity of the VSL, which is set at 1.3. Using Equation (4), Bui et al. (2021) find the VSL of Vietnam in 2011 to be \$0.261 (million US dollars). We then use the changes in consumer price indexes and real GDP per capita between 2011 and 2020 to calculate the VSL in 2020 as follows

$$VSL_{VNM,2020} = VSL_{VNM,2011} \times \left(1 + \Delta P_{2011,2020}\right)^{e} \times \left(1 + \Delta Y_{2011,2020}\right)^{e} \quad (5)$$

where ΔP and ΔY are the percentage increase in consumer price indexes and real GDP per capita between 2011 and 2020, taken from the World Bank's World Development Indicators database.

Using Equation (5), we find the VSL to be \$0.718 million US dollars in 2020. Finally, multiplying the VSL with the reduced number of deaths (99 for both NO_2 and $PM_{2.5}$; Table 4, Panel A), we obtain the monetary benefits of \$71.1 million US dollars from lower mortality (Panel B). We consider this estimate to be the upper bound, since Viscusi and Masterman (2017) offer a lower VSL of \$0.342 million US dollars for Vietnam. Using their VSL, we obtain the lower bound estimate of \$33.9 million US dollar from lower mortality (Panel B). Applying a similar exercise to calculate the monetary benefits resulting from a lower number of hospital admissions (also after updating Bui et al.'s (2021) results from 2011 to 2020), we obtain an estimate of \$0.02 million US dollars (Panel B). Consequently, the total monetary benefits from reduced mortality and hospital admissions due to improved air quality ranges from \$33.92 to \$71.12 million US dollars.

To calculate the economic losses during the two weeks under the lockdown for Vietnam, we combine the World Bank's pre-COVID-19 projected economic growth rate of 6.5 percent in 2020 (World Bank, 2020) and the 2019 GDP ($262 billion US dollars) to estimate the hypothetical projected GDP in 2020 in the absence of the pandemic.[10] We then compare this projected figure against the actual GDP based on the actual growth (0.39 percent) in the second quarter of 2020 (GSO, 2021a) (that spans the lockdown); the difference between the projected and actual GDP values would be the loss caused by the pandemic.[11]

Our estimates show that the prorated monetary losses associated with a two-week pandemic-induced lockdown period are roughly $615.7 million US dollars (Table 4, Panel C). This ranges from 9 to 18 times larger than the economic gains coming from improved air quality discussed above (Table 4, Panel B). Yet, the economic gains discussed above are conservative since they do not take into account the beneficial impacts from improved air quality on other diseases and longevity (Liu et al., 2019; WHO, 2016), or negative externalities ranging from reducing crop yields, lowering property values to steering talented workers away from polluted places (World Bank, 2016). Furthermore, there are also the general non-monetary benefits of a cleaner environment and better quality of life that all individuals can enjoy.[12]

Finally, it is useful to briefly compare our estimated lockdown effects on air pollution with those of other environmental regulations found in the literature. For example, Auffhammer and Kellogg (2011) show that the introduction of the California Air Resources Board (CARB) gasoline regulations in the US reduces air pollution by more than 20 percent. Similarly, recent studies in China find that enforcing more stringent fuel standards improves air quality by 12.9 percent (Li, Lu, and Wang, 2020) and replacing coal with cleaner energy increases air quality by 36 percent (Fan, He, and Zhou, 2020). We note while the lockdown impact magnitudes are comparable, lockdown effects are more short-lived than those found in these studies.

6. Discussion and Conclusion

Together with economic growth, Vietnam has witnessed steadily and alarmingly rising levels of air pollution, which can lead to public health challenges. This underscores the importance of evaluating policies that have the potential to improve air quality. The COVID-19 pandemic provides an unprecedented opportunity for us to do just that, which is to investigate how air quality changes in response to lockdown policies. In particular, in order to curb COVID-19 infection, the government has put in place containment measures which have ranged from school closures and cancellations of public gatherings to restrictions on mobility.

Our empirical analysis reveals that the COVID-19-induced lockdown significantly reduces air pollution in Vietnam. However, the impacts dissipate ten weeks after the lockdown. This short-lived duration of impact should perhaps be expected since the lockdown was implemented during only two weeks. We also find that the lockdown effects are greater in districts without coal power stations and cement plants, or with less industrial or agricultural production. The estimated magnitudes of reduced air pollution are comparable to those found in previous studies on stricter gasoline regulations or transition to cleaner energy sources, suggesting that measures in these directions may help the country improve its air quality and achieve a sustainable growth trajectory. Similarly, a switch to high-precision and organic agriculture may also result in positive effects on air quality. These are consistent with recent observations that while COVID-19 is a public health emergency, it also offers a real-time experiment in downsizing the consumer economy and makes a strong case for a sustainability agenda (Perkins et al., 2021; Sarkis et al., 2020).

We also investigate the mediating role of human mobility in the relationship between lockdown policies and air pollution. We find that sharp reductions in human mobility are strongly associated with the lockdown, which implies that these activities could be important sources of air pollution. This also highlights the importance of better control over emissions from these sources when the economy returns to normal. Our cost-benefit analysis reaffirms the significant health and economic effects of air pollution. Environmental policies that aims at reducing air pollution can reduce the associated mortality and hospitalization rates, at least in the short run. Finally, our calculations provide tentative evidence that the economic gains from improvements in air quality are just a small fraction (i.e., ranging from six to 12 percent) of the economic losses caused by the lockdown. But these calculations do not take into account non-monetary health benefits and better quality of life.

Notes

1. See Bloom, Kuhn, and Prettner (2020) and Brodeur, Gray, Islam, and Bhuiyan (2021) for recent reviews of the economics literature on COVID-19.
2. The RDD model is considered more rigorous than the difference-in-differences model used in most existing studies.
3. Other studies offer qualitatively consistent results. For example, Luong et al. (2017) find an increase of 10 $\mu g/m^3$ in $PM_{2.5}$ to be associated with a 2.2-percent higher risk of hospital admission for young children in Hanoi. Analyzing 57,851 hospital admissions over eight years in Hanoi, Nhung et al. (2018) also show that more concentration of NO_2 is associated with pneumonia-related hospitalizations.
4. Vietnam has 63 provinces, which are further divided into around 700 districts. According to the 2019 Population and Housing Census, the average district's area and population are 469.85 (km^2) and 125,530, respectively.
5. Incidentally, we also collect data on the national lockdown dates for a number of countries for external validity analysis. These are shown in the Supplementary Online Materials.
6. Except for the province fixed effects, we suppress the province index in all the equations for less cluttered notation. Note that provinces and districts are respectively the first-level and second-level administrative divisions.
7. We do not provide the standard RDD tests of covariate balance (or sorting) since these are not feasible under the RDiT approach where time is the running variable (Hausman & Rapson, 2018).
8. This share is approximately 9.4 percent according to the 2020 Vietnam Statistical Yearbook (GSO, 2021c).
9. These estimates are comparable to those found in studies in richer countries. For example, Janke (2014) shows that a one-percent increase in NO_2 increases hospital admissions by 0.1 percent in England.
10. Alternatively, we use the 5-year average GDP growth for 2015-2019 (6.7 percent) and find a similar estimate of economic losses (635.8 million US dollars).
11. Figure A7 (Supplementary Material) shows that the growth rate in the second quarter of 2020 (spanning the lockdown period) was far below the relatively stable growth rate of roughly 6 percent for the same quarter in the preceding four years.
12. We focus in this study on the monetary benefits from improved air quality and do not consider other positive externalities on reduced fatality due to the lockdown (and its associated measures such as social distancing or quarantines).

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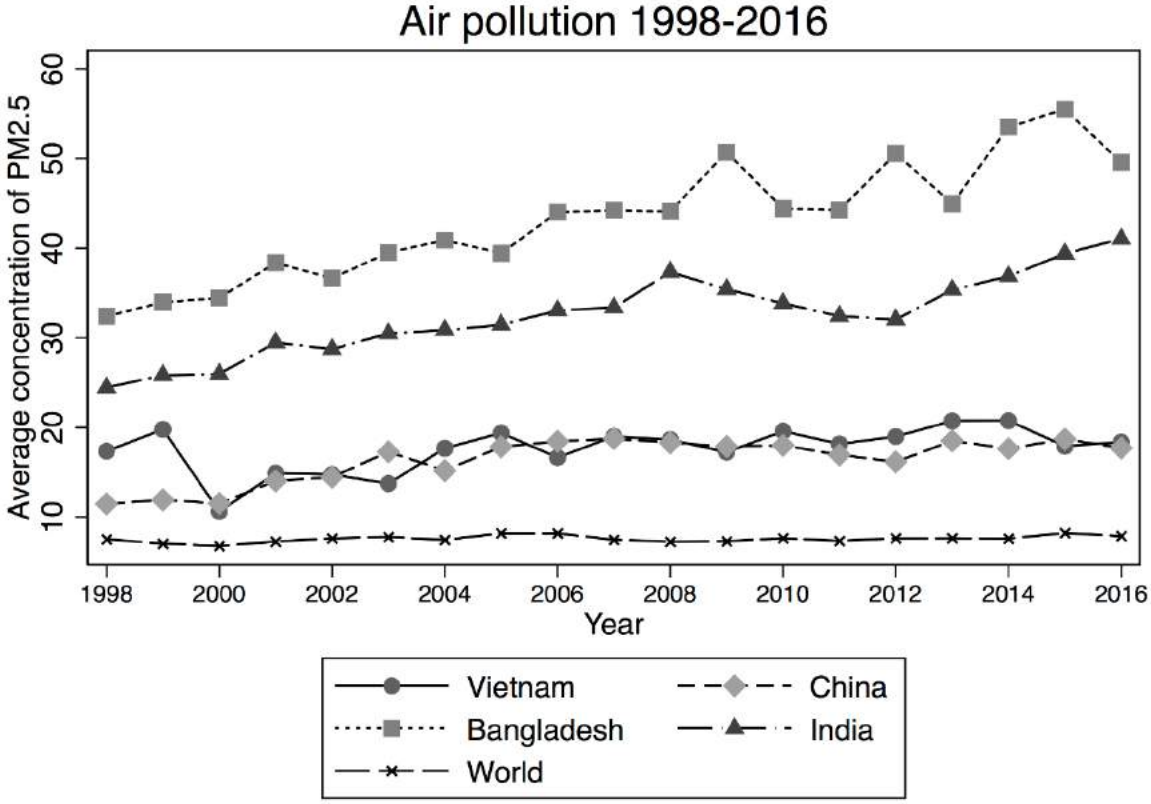
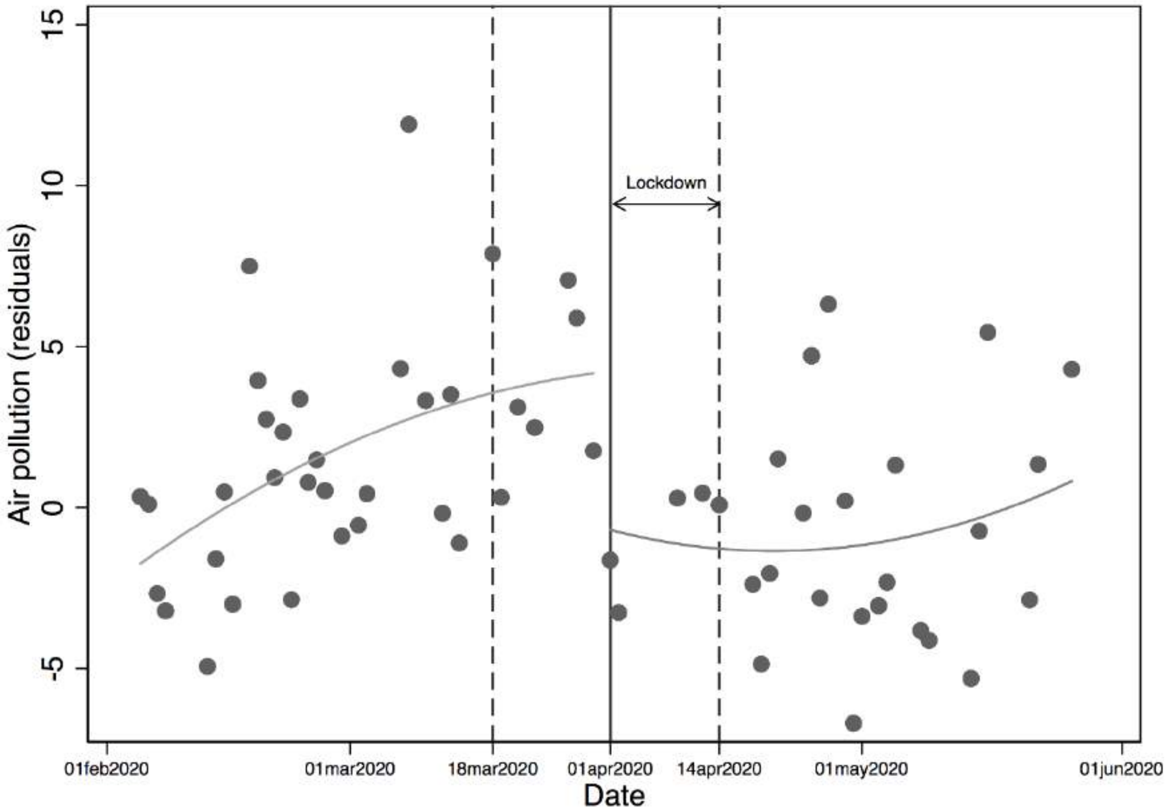
Figure 1: Long-term air pollution



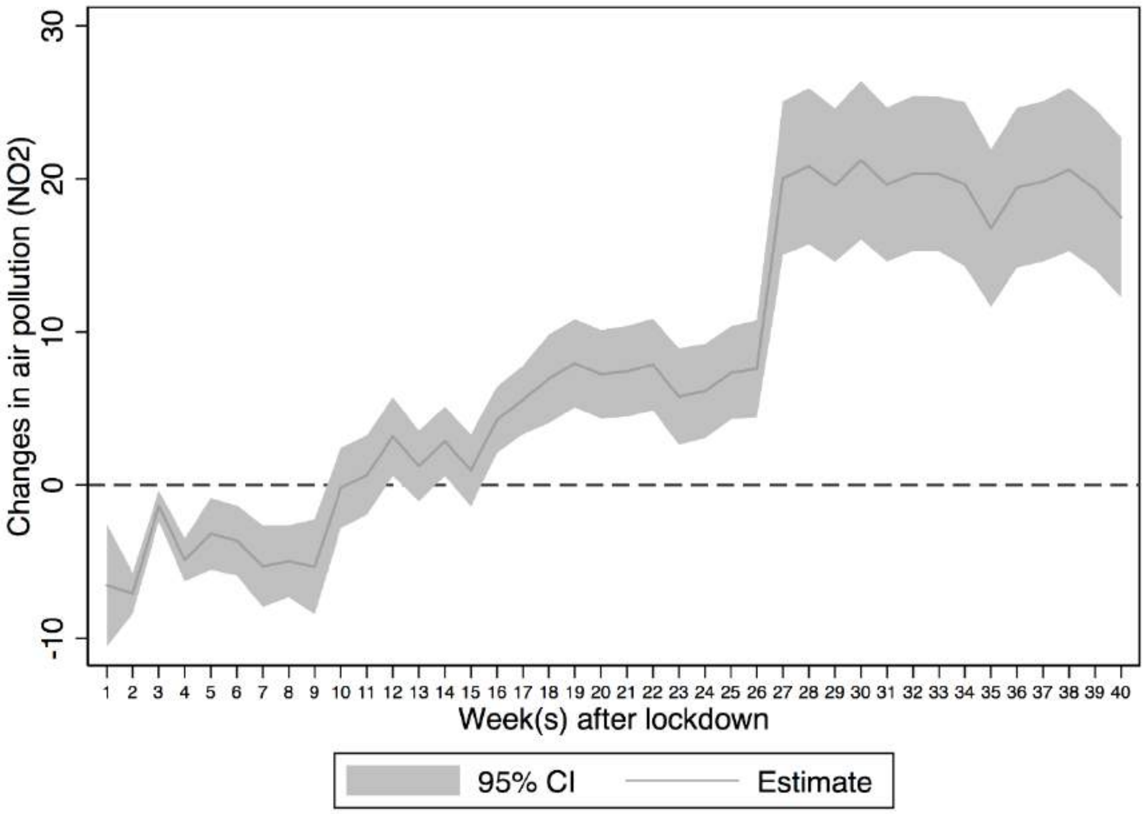
Notes: Air pollution is measured by mean annual $PM_{2.5}$ exposure (micrograms per cubic meter). The data are derived from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS).

Figure 2: Air pollution before, during, and after the lockdown



Notes: The plotted dots are predicted residuals from estimating air pollution (NO_2) with province and time fixed effects. The dash lines represent two weeks before and after the official lockdown date.

Figure 3: Changes in air pollution after lockdown



Notes: Air pollution is measured by NO_2 from satellite data. Each point in the figure shows point estimate and 95 percent confidence interval of treatment variable (lockdown) using different bandwidths after the lockdown. The parametric RDD model includes interactions of running variable (linear and quadratic terms) with treatment variable. The running variable is number of days from the lockdown date. All regressions include province dummies and month dummies. Control variables are daily temperature and precipitation.

Table 1: COVID-19 lockdowns and air pollution – Main results

Air quality:	+/-2 weeks		+/-4 weeks		+/-8 weeks	
NO_2	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Linear model						
Lockdown=1	-6.126***	-5.808***	-4.807***	-4.977***	-4.289***	-4.724***
	(0.448)	(0.443)	(0.610)	(0.598)	(1.110)	(1.120)
Panel B: Linear interaction model						
Lockdown=1	-5.670***	-5.059***	-4.900***	-5.052***	-4.218***	-4.716***
	(0.447)	(0.442)	(0.618)	(0.605)	(1.104)	(1.118)
Panel C: Quadratic model						
Lockdown=1	-6.297***	-6.139***	-5.086***	-5.196***	-4.221***	-4.724***
	(0.435)	(0.432)	(0.643)	(0.629)	(1.104)	(1.120)
Panel D: Quadratic interaction model						
Lockdown=1	-7.696***	-7.824***	-5.444***	-5.426***	-4.216***	-4.690***
	(0.671)	(0.668)	(0.737)	(0.724)	(1.104)	(1.118)
Means before lockdowns	24.441	24.441	27.579	27.579	25.369	25.369
Controls	No	Yes	No	Yes	No	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,524	3,518	8,636	8,620	22,962	22,851

Notes: *** p<0.01, ** p<0.05, * p<0.1. Results of parametric RDD. Clustered standard errors in parentheses are robust to within-day and within-district serial correlation. Air pollution is measured by NO_2 (mole per square kilometer) from satellite data. Running variable is number of days from the lockdown date. Model 1 uses running variable in linear form, Model 2 includes interaction of running variable and treatment variable, Model 3 includes quadratic term of running variable, Model 4 includes interactions of running variable (linear and quadratic terms) with treatment variable. All regressions include province dummies and month dummies. Control variables are daily temperature and precipitation.

Table 2: COVID-19 lockdowns and air pollution – Power stations and cement plants

Air pollution:	(1)	(2)	(3)
NO_2	+/-2 weeks	+/-4 weeks	+/-8 weeks
Panel A: Coal-fired stations			
Lockdown*No coal-powered plants	-9.218***	-10.621***	-8.752***
	(3.136)	(2.771)	(1.708)
Panel B: Cement plants			
Lockdown*No cement plants	-6.885***	-0.450	-2.368**
	(1.939)	(1.527)	(0.949)
Panel C: Coal-fired and cement plants			
Lockdown*No coal-powered and no cement plants	-10.454***	-2.948**	-3.828***
	(1.731)	(1.403)	(0.872)
Controls	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	3,518	8,620	22,851

Notes: *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Results of parametric RDD that includes interactions of running variable (linear and quadratic terms) with treatment variable. Clustered standard errors in parentheses are robust to within-day and within-district serial correlation. All regressions include province dummies and month dummies. Control variables are daily temperature and precipitation.

Table 3: COVID-19 lockdowns and mobility restriction

Mobility changes	Retail and recreation	Grocery and pharmacy	Park	Transit	Workplaces	Residential
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: +/-2 weeks						
Lockdown=1	-13.758***	-17.141***	-9.999***	-16.014***	-18.438***	4.870***
	(0.927)	(0.911)	(1.331)	(1.119)	(1.023)	(0.331)
Observations	1,763	1,705	1,758	1,663	1,763	1,697
Panel B: +/-4 weeks						
Lockdown=1	-26.676***	-19.955***	-13.609***	-22.759***	-23.877***	7.708***
	(0.781)	(0.704)	(1.001)	(0.903)	(0.681)	(0.242)
Observations	3,527	3,406	3,512	3,304	3,527	3,410
Panel C: +/-8 weeks						
Lockdown=1	-29.215***	-23.369***	-13.855***	-29.339***	-33.502***	10.040***
	(0.472)	(0.453)	(0.599)	(0.615)	(0.559)	(0.170)
Observations	6,419	6,209	6,384	5,956	6,420	6,247

Notes: *** p<0.01, ** p<0.05, * p<0.1. Results of parametric RDD that includes interactions of running variable (linear and quadratic terms) with treatment variable. Clustered standard errors in parentheses are robust to within-day and within-province serial correlation. Control variables are daily temperature and precipitation.

Table 4: COVID-19 lockdowns and air pollution – Cost-benefits analysis

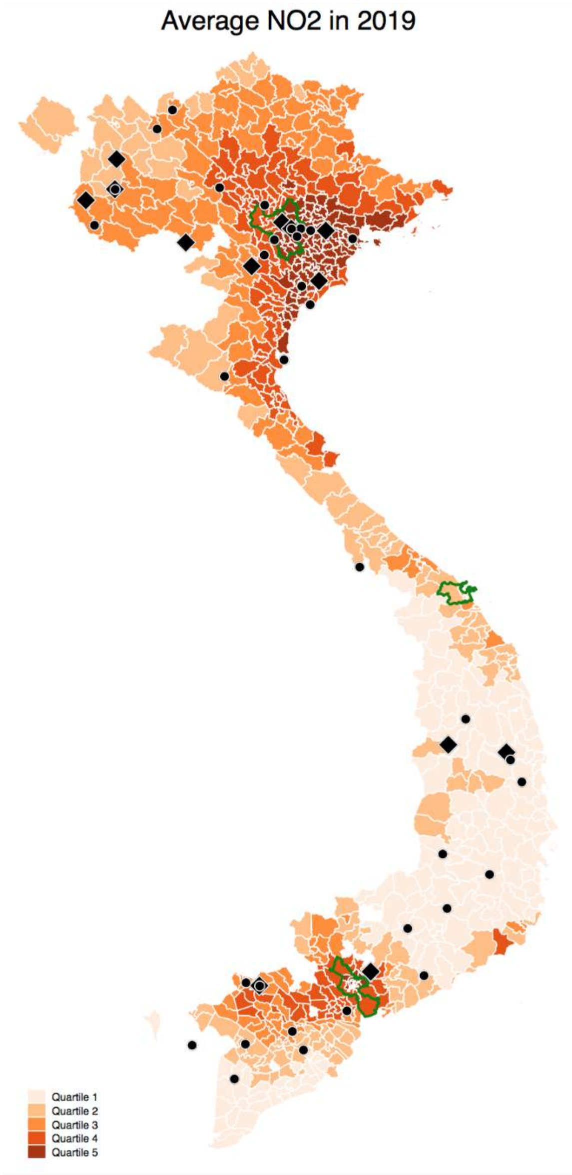
	Estimates
Panel A: Health benefits	
Decrease in mortality	99 (persons)
Decrease in hospital admissions	234 (persons)
Panel B: Economic benefits	
Decrease in mortality	33.9 – 71.1 (million US dollars)
Decrease in hospital admissions	0.02 (million US dollars)
Panel C: Economic losses	
Estimated losses	615.7 (million US dollars)

Notes: We use the mid-point of our estimated decreases of between 24-32 percent in Table 1 (i.e., 28 percent) in NO_2 concentration and the associated 17 percent reduction in $PM_{2.5}$ concentration using Dang and Trinh's (2021) results.

Online Supplementary Materials

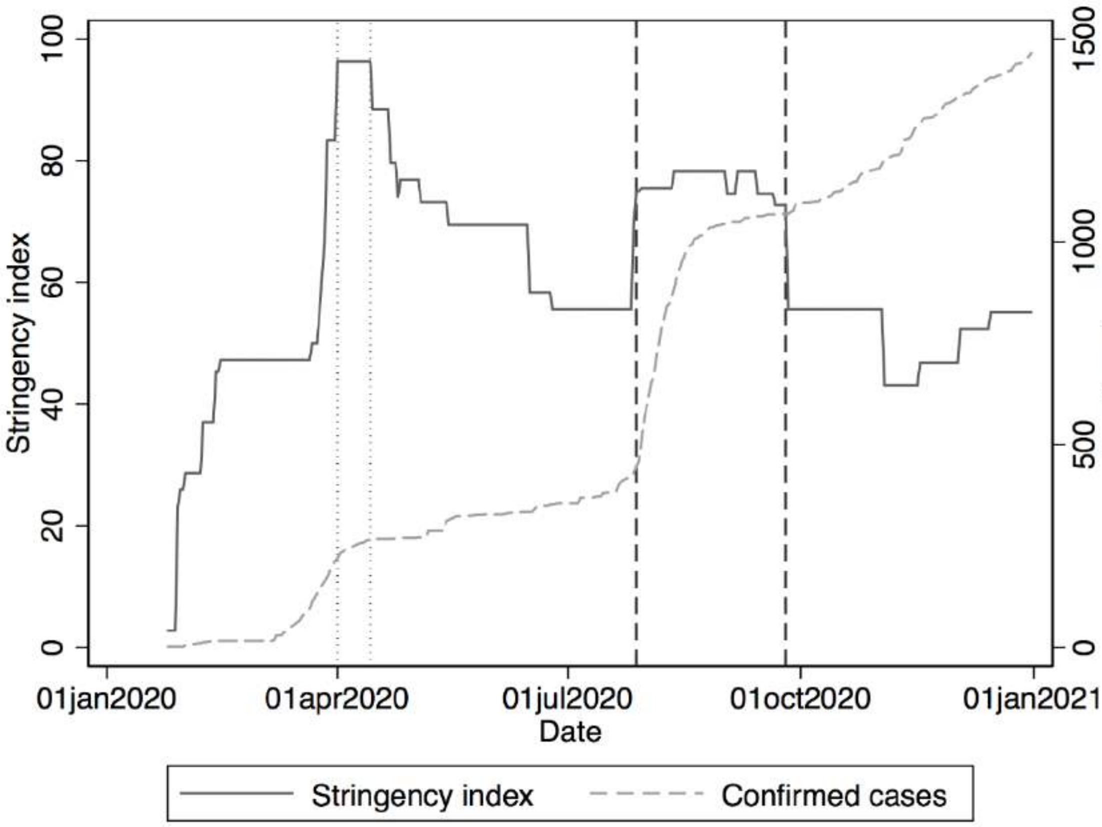
Part A: Additional Figures and Tables

Figure A1: Air pollution in Vietnam in 2019



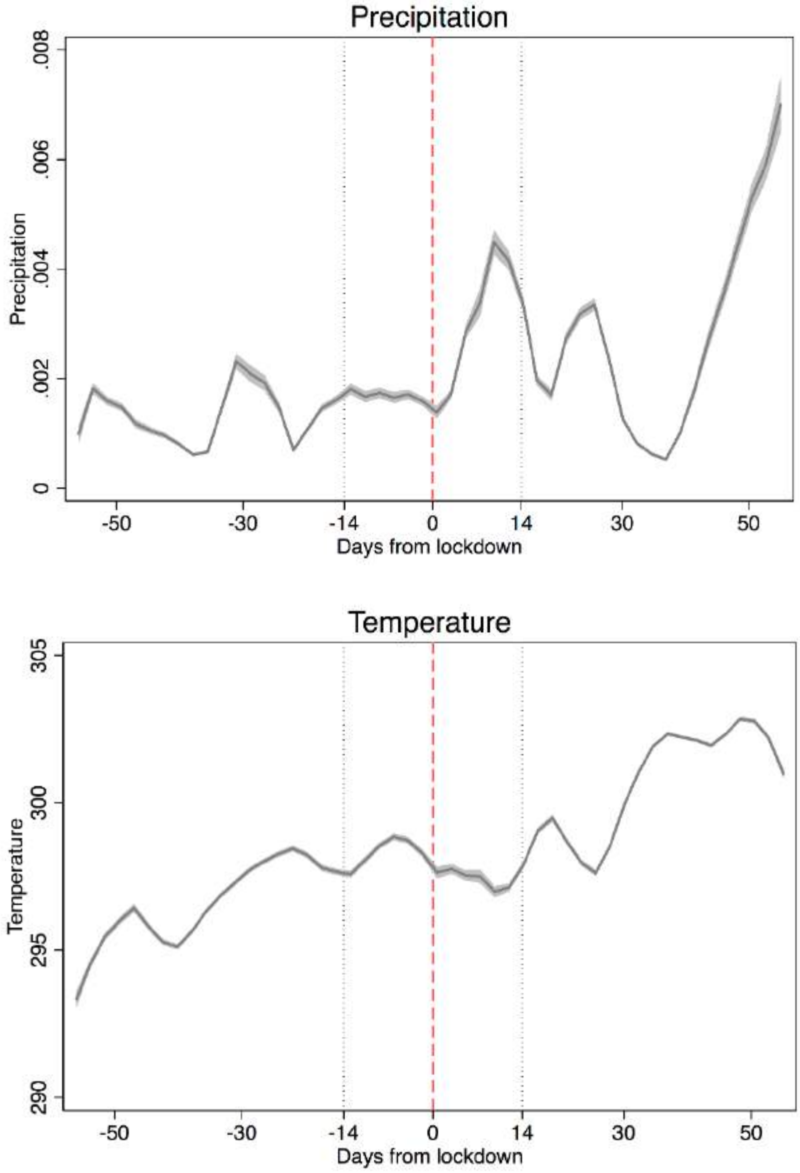
Notes: Average NO_2 is taken from satellite data. Darker values represent higher concentration of NO_2. Areas with green border represent three big cities in Vietnam (Hanoi, Da Nang, and Ho Chi Minh City). Two islands of Vietnam, Hoang Sa and Truong Sa, are not presented in this map. Locations of coal-fired power stations and cement plants are marked with black diamond and black dot, respectively.

Figure A2: Stringency index and confirmed cases



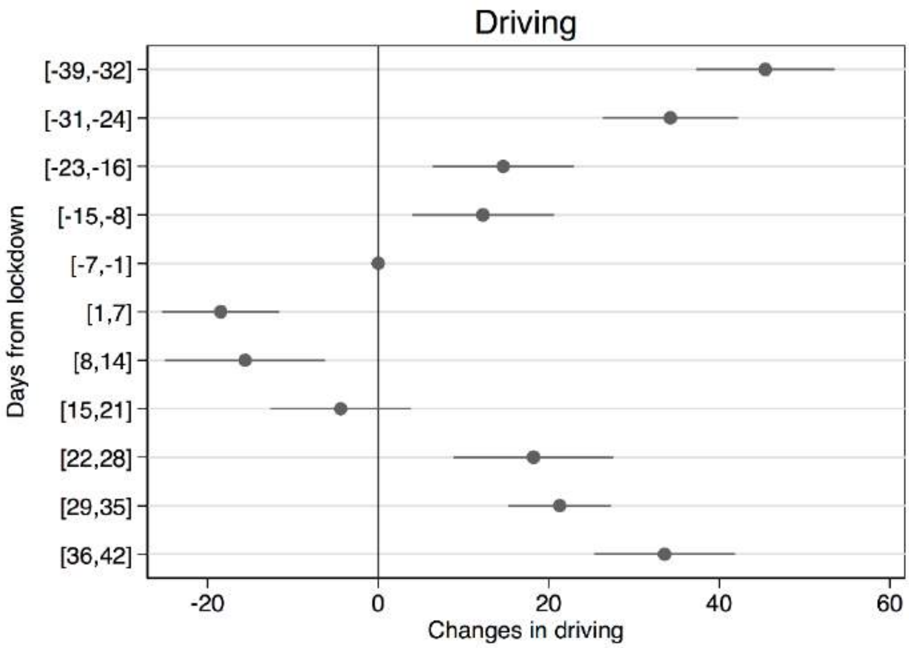
Notes: The data is derived from Oxford COVID-19 Government Response Tracker (OxCGRT). The vertical dot lines represent national lockdown period in Vietnam (April 1 – April 14), while the vertical dash lines represent regional lockdown period from July 31 to 29 September.

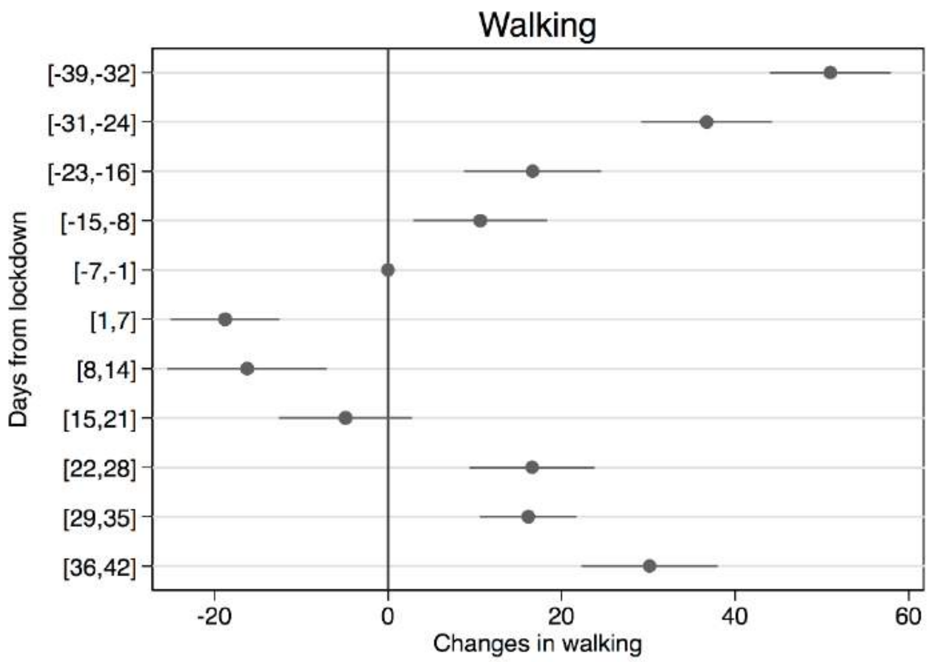
Figure A3: COVID-19 lockdowns and temperature/precipitation



Notes: Temperature and precipitation data are derived from the National Center for Environmental Prediction (NCEP) at the National Oceanic and Atmospheric Administration (NOAA). The continuous line is the predicted outcome from RDD regression using the optimal bandwidths based on Imbens and Kalyanaraman (2012). The lockdown period is shown in the dot lines.

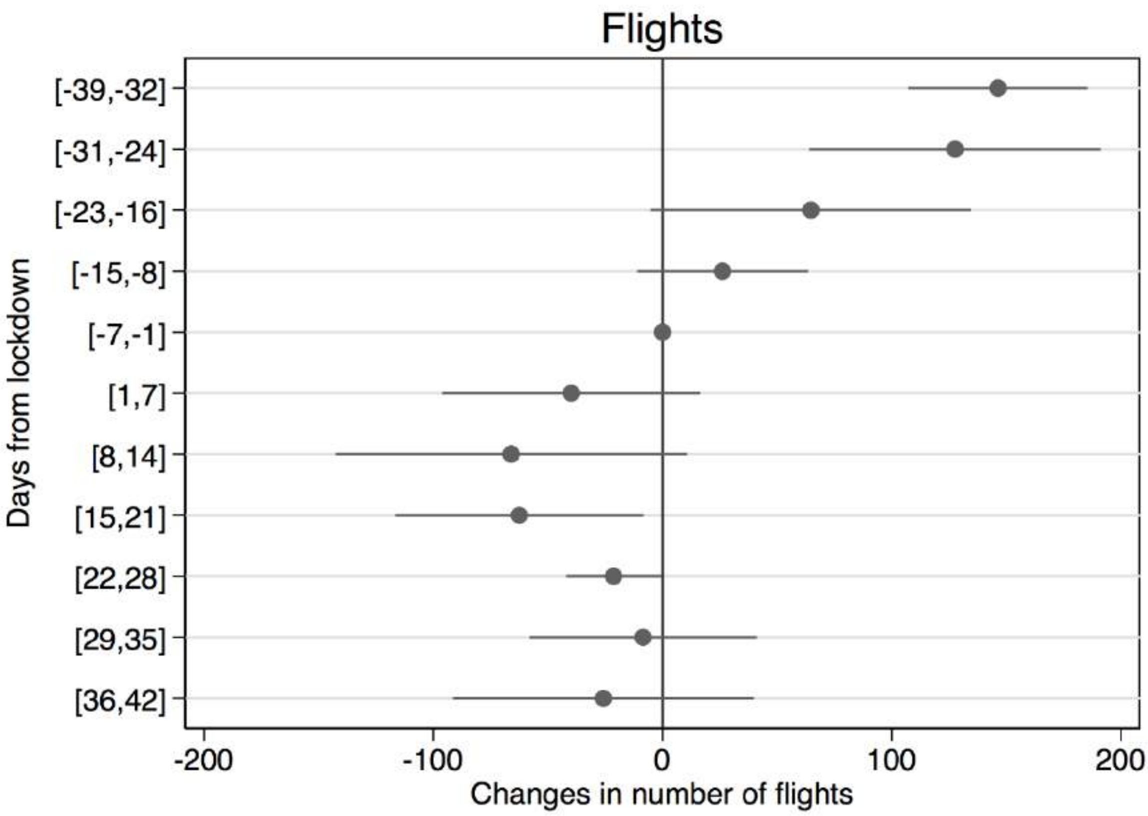
Figure A4: COVID-19 lockdowns and mobility restriction – Apple mobility data





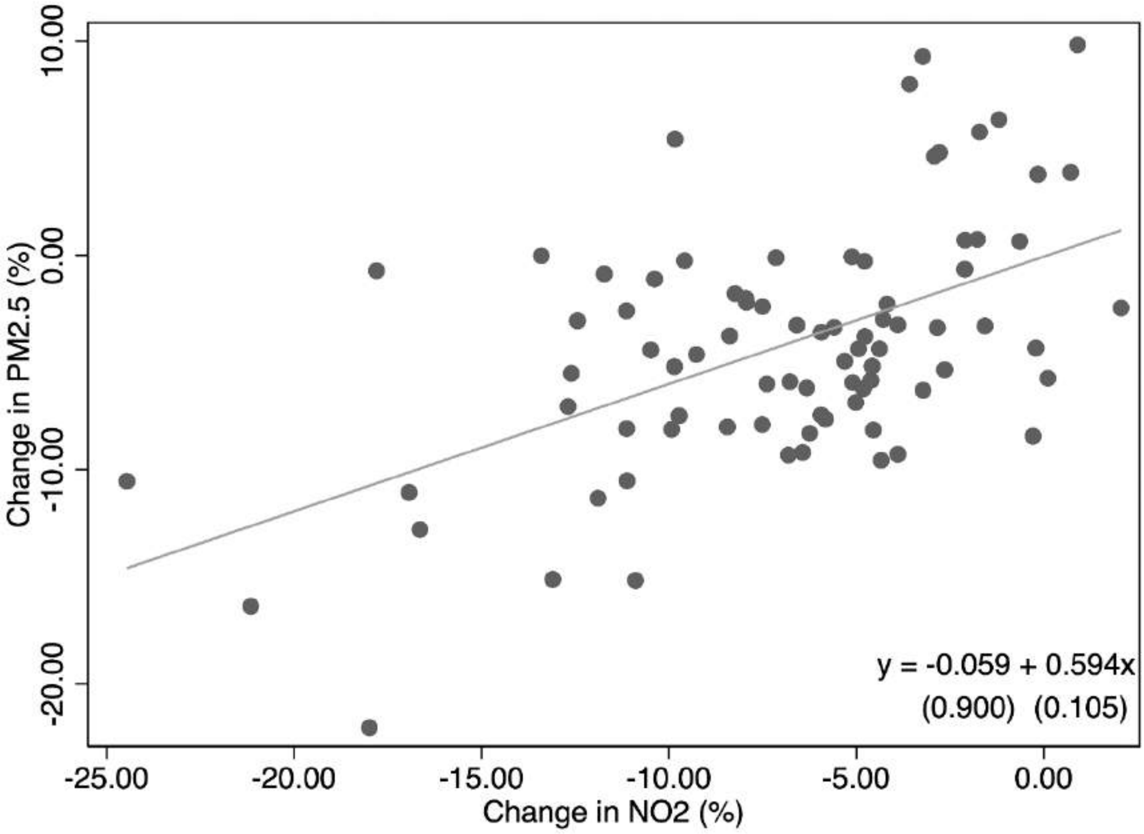
Notes: Figure reports effects of lockdowns and confidence intervals from time-event analysis, with time fixed effects. Control variables are daily temperature and rainfall. The reference group is one week before the lockdown date. Apple COVID-19 Mobility Trends Reports are available at https://www.apple.com/covid19/mobility/

Figure A5: COVID-19 lockdowns and number of flights



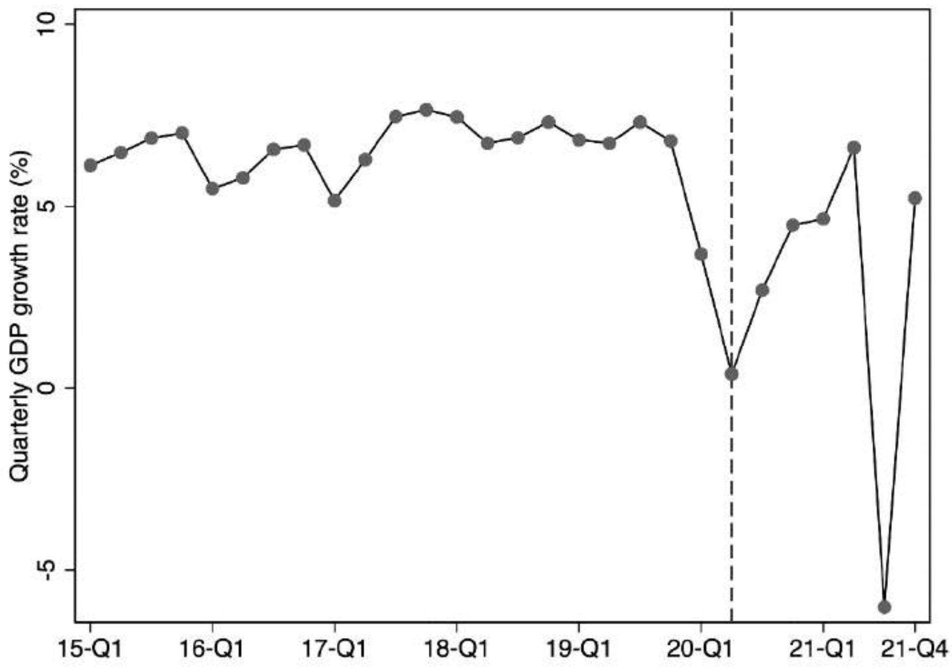
Notes: Figure reports effects of lockdowns and confidence intervals from time-event analysis, with time fixed effects. Control variables are daily temperature and rainfall. The reference group is one week before the lockdown date. Flights data are available at https://www.vietnamairport.vn/en/

Figure A6: Changes in NO_2 and $PM_{2.5}$ during the COVID-19 lockdown



Notes: Data is taken from Dang and Trinh (2021). Estimated coefficients are shown from an OLS regression of the change in $PM_{2.5}$ on the change in NO_2. Standard errors are in parentheses.

Figure A7: Vietnam quarterly GDP growth rate 2015 – 2021



Notes: Data are from the General Statistical Office of Vietnam (GSO, 2021). The dash line represents the quarter under the national lockdown.

Table A1: COVID-19 lockdowns and air pollution – Other parameters of pollution

Bandwidths	+/-2 weeks	+/-4 weeks	+/-8 weeks
	(1)	(2)	(3)
Panel A: Air quality is measured by CO			
Lockdown=1	-0.006***	-0.003***	-0.001
	(0.001)	(0.000)	(0.001)
Means before lockdowns	0.059	0.057	0.052
Observations	13,376	25,988	53,857
Panel B: Air quality is measured by SO_2			
Lockdown=1	0.291*	-0.343	-4.352***
	(0.165)	(0.445)	(0.650)
Means before lockdowns	0.257	0.228	0.594
Observations	852	3,052	9,023
Panel C: Air quality is measured by O_3			
Lockdown=1	3.529***	0.096***	-0.138***
	(0.859)	(0.026)	(0.027)
Means before lockdowns	11.854	11.632	11.513
Observations	1,339	5,569	16,320
Controls	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes

Notes: *** p<0.01, ** p<0.05, * p<0.1. Results of parametric RDD that includes interactions of running variable (linear and quadratic terms) with treatment variable. Clustered standard errors in parentheses are robust to within-day and within-district serial correlation. Air pollution parameters are taken from satellite data. All regressions include province dummies and month dummies. Control variables are daily temperature and precipitation.

Part B: Data Appendix, Robustness Checks, and Further Analysis

1. Data Appendix

We obtain air pollution measurements in Vietnam from January 1, 2020 to January 10, 2021, provided by the National Aeronautics and Space Administration (NASA) and European Space Agency (ESA). In particular, we use data from the Sentinel-5P/TROPOMI (S5P) instrument of the European Union's Copernicus programme. The S5P satellite uses spatial resolution of 5.5 km and provides a (near-)global coverage of air pollution caused by NO_2 and other pollutants such as O_3, SO_2, and CO.[2] We use Google Earth Engine to process and average air quality parameters at the district level using administrative areas of Vietnam taken from Database of Global Administrative Areas (GADM). We use NO_2 as the main measure of air pollution for two reasons. First, NO_2 is a highly reactive pollutant and considered highly lethal to human health (Faustini, Rapp, & Forastiere, 2014). It is also the leading source of childhood asthma in urban areas globally (Achakulwisut, Brauer, Hystad, & Anenberg, 2019). Second, NO_2 has a short lifetime which implies that its molecules stay fairly close to their sources and thus offer an appropriate measure of changes in emissions.[3] We then perform a cloud masking which excludes results from pixels with > 10 percent cloud fraction. This addresses the issue of cloud cover which may obscure the sensor's view of the lower atmosphere.

Given that concentrations of NO_2 in the atmosphere are highly variable and sensitive to changes in weather conditions, we collect daily temperature and precipitation as control variables. The data are available from the National Center for Environmental Prediction (NCEP) at the National Oceanic and Atmospheric Administration (NOAA). The global dataset provides four 6-hour daily records of temperature and precipitation at the resolution of approximately 25 km. We then extract the weather data at the district level using a similar process as with the air pollution data.

To investigate differential impacts of COVID-19 on air pollution, we obtain the list of coal-fired stations and cement plants from multiple sources. We focus on those that are operating by the time of 2019. For other heterogeneity tests, we collect information on industrial production from the Statistical Yearbook of Vietnam, published by the General Statistical Office of Vietnam (GSO). The GSO provides two measures of industrial production including industrial production index and foreign direct investment (FDI). The former indicator is calculated as the percentage of the quantity of industrial production generated in a given year compared to the base year, while the latter indicator measures accumulation of FDI projects having effect as of 2019. Both indicators are available at the province level.

We also use monthly nightlight data from NOAA as alternative measure for industrial production. Satellite nightlight have been widely used in the economic literature as a proxy for numerous economic, social and environmental indicators (e.g., Henderson, Storeygard, & Weil, 2012; Hodler & Raschky, 2014). We use data from the Suomi National Polar-Orbiting Partnership system (SNPP/VIIRS) system, which provides high resolution of nightlight (450m by 450m). We then calculate average nightlight in 2019 at the district level. Prior to averaging, the data are filtered to exclude data impacted by stray light, lightning, lunar illumination, and cloud-cover.

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[2] We do not use station-based data to examine these measures due to small number of stations recorded in the database.

[3] NO_2 is recommended by the European Union's Copernicus programme as the most appropriate indicator of air pollution. For more details, see: https://atmosphere.copernicus.eu/flawed-estimates-effects-lockdown-measures-air-quality-derived-satellite-observations?q=flawed-estimates-effects-lockdown-measures-air-quality-satellite-observations. We analyze the S5P satellite data since they are available around the lockdown date of April 2020 for Vietnam.

We also collect data on public perceptions about environment from the Provincial Governance and Public Administration Performance Index (PAPI). PAPI is calculated from surveys conducted annually by the Centre for Community Support Development Studies (CECODES), the Fatherland Front, and the United Nations Development Programmes (UNDP). The survey uses a clustered random sampling approach, starts from 2009 and covers all provinces of Vietnam from 2011. PAPI collects information from a sample of over 13,000 individuals each year regarding their experiences with multiple dimensions of governance. In this paper, we are interested in indicators of individual experiences and perceptions on environmental governance, namely environmental protection and quality of air.

To check robustness of our findings, we obtain information on government response indexes from the Oxford COVID-19 Government Response Tracker (OxCGRT). This tracker implemented by the University of Oxford's Blavatnik School of Government systematically collects information on policy stringency taken by governments to tackle the pandemic since February 2020 (Hale, Petherick, Phillips, & Webster, 2020). OxCGRT collects information on government policy responses across eight dimensions, namely: (i) school closures; (ii) workplace closures; (iii) public event cancellations; (iv) gathering restrictions; (v) public transportation closures; (vi) stay-at-home orders; (vii) restrictions on internal movement; and (viii) international travel bans. These dimensions are then used to calculate response indexes to COVID-19. Each index is rescaled to get a score between 0 and 100 (100 representing the highest degree of strictness/restriction). We employ different indexes from the OxCGRT data including (i) the stringency index, (ii) the government response index, and (iii) the containment and health index.[4]

We collect data on human mobility from February 15, 2020 to January 10, 2021, using the freely available Google COVID-19 Community Mobility Reports (GCMR) dataset. The GCMR reports mobility as percentage changes relative to a baseline period (from January 3 to February 6, 2020). Absolute mobility values are not available to protect users' privacy. The data account for weekly seasonality of movement by estimating a set of seven baseline weekdays using the median value for each particular weekday during the 5-week baseline period. Daily relative change is estimated as the percentage change with respect to the corresponding baseline weekday for any given report date. In Vietnam, the GCMR data are aggregated at the province level, and by category of place (e.g., supermarket and pharmacy, workplaces, residential). We expect that the lockdown will lead to reduced mobility of all categories, except for the residential. We also use mobility reports released by Apple. The dataset provides statistics of daily changes in driving and walking direction requests from its users in two big cities in Vietnam (Hanoi and Ho Chi Minh City). Finally, we collect flight data provided by the Airports Corporation of Vietnam. The data contains number of daily domestic and international flights from all the eight international airports in Vietnam. The descriptions and summary statistics of variables used in our analysis are listed in Table B1 below.

2. Robustness Checks

Our results are robust to a number of sensitivity checks which we discuss next. First, our main analysis employs the parametric RDD model to estimate Equation (2) and our main window of time is two weeks before and after the lockdown. Alternatively, we supplement these estimates by estimating a nonparametric RDD model using the local linear regressions (LLR) suggested by Hahn, Todd, and Van der Klaauw (2001). This method helps reduce the

[4] The OxCGRT data also calculates economic support index. Our analysis does not use this measure as it only includes income support programs and debt relief programs and does not fully capture the overall responsiveness of the government to COVID-19.

estimation bias that can result from analyzing observations that are further away from the threshold (Calonico, Cattaneo, Farrell, & Titiunik, 2019; Lee & Lemieux, 2010). We use different methods to calculate the optimal bandwidth suggested by Imbens and Kalyanaraman (2012), Calonico, Cattaneo, and Titiunik (2014) and Lee and Lemieux (2010). We report the estimation results in Table B2, which are consistent across different optimal bandwidths. The magnitudes of the estimated impacts are also comparable to those in our main specifications.

Second, we conduct a number of placebo tests by using different "fake" treatment dates to verify our RDiT specifcation. We assume the date of lockdown to be 1, 2, 3, and 4 weeks prior to the actual date, and it is also assumed to be one year earlier than the actual timing. Given that there was no real lockdown implementation at those plabebo dates, the main outcome should be smooth across the cutoff. Indeed, the results in Table B3 show that the coefficients on lockdown variable are statistically insignificant which lend support to our main specification.

Third, the RDiT approach involving time may be confounded by the effects of sorting and anticipation. For example, knowing the lockdown is to be implemented, individuals may response in advance to the shutdown of economy. To address such concerns, following Barreca, Guldi, Lindo, and Waddell (2011), we implement a "donut" RDD specification where we use the bandwidth of eight weeks from the lockdown date and exclude observations in 1, 2, and 3 weeks around the cut-off. The estimation results are reported in Table B4. The key coefficients remain negative and statistically significant, suggesting that the RDD specification is not contaminated by any anticipation effect. Also, we extend our RDiT framework by including the lagged dependent variable as an additional control variable in the regressions. This approach allows us to address potential serial correlation that arises in the RDiT framework (Hausman & Rapson, 2018). Again, we find consistent results with our main findings, as shown in Table B5.

Fourth, to account for the (remote) possibility that the economy may not completely shutdown by the time of the lockdown, we employ a fuzzy RDD model to provide robustness checks. As discussed earlier in section 4, the strictness of the implementation of the lockdown can be measured by government responses indexes from the OxCGRT database.[5] We estimate the IV model in Equations (3) and (4), with our instrument being a dummy variable equal to one for the response indexes being positive and the government responses indexes being the running variable. We analyze the period of January 1, 2020 and January 10, 2021, when OxCGRT provides these indexes. The estimation results of the fuzzy RDD model, shown in Table B7, are consistent with our main findings in Table 1.

Fifth, as an alternative to the changes in air pollution levels, we convert these changes to the logarithmic form. The estimation results, shown in Table B8, remain qualitatively similar. Finally, one possible concern is that differences in province-specific resources and policies may result in differential provincial time trends in air pollution. To account for this, we include the interaction terms for the dummy variables for 63 provinces in Vietnam with the linear time trends. The results, presented in Table B9, are generally consistent with our main findings.

3. Further Analysis

The effects of COVID-19 lockdown on air pollution may vary by province and district characteristics. To shed more light on this issue, we first explore the question whether the lockdown has differential effects on locations with and without coal-fired power stations. Previous studies have confirmed the adverse health impact of emissions from coal plants. For example, Fan, He, and Zhou (2020) show that turning on the winter heating system leads to 14

[5] Table B6 provides further details regarding components of OxCGRT indexes.

percent increase in mortality rate in China. Similarly, Luechinger (2014) finds that desulfurization at power plants results in an annual gain of 826–1460 infant lives. Since coal-fired power stations were allowed to be in normal operation during the lockdown like most other manufacturing activities (GoV, 2020), locations without these power stations would likely have recorded more reduced air pollution after the lockdown. The estimation results, shown in Table 2, Panel A, confirm our expectation.

Similarly, we would expect that locations without cement plants would likely have more decreased air pollution, which is supported by the estimation results in Table 2, Panel B. Furthermore, locations with neither coal-powered stations nor cement stations have even more reduced air pollution in the two-week period after the lockdown as well as over longer periods (Table 2, Panel C). Yet, one may argue that it is the capacity of these stations—rather than their numbers—that determines the levels of pollution. Therefore, we provide estimates using the capacities of coal-powered and cement stations in Table B10, which offers a qualitatively similar conclusion. But as a note of caveat, the magnitudes of the estimated impacts in Table 2 should be interpreted with caution since we do not have information on the exact degree that operations of these stations were affected by the lockdown.

We next examine a related question of whether the less industrialized locations have more reduced air pollution after the lockdown. To answer this question, we interact the lockdown variable with indicators of industrial production. We start with an industrial production index, followed by two alternative measures, FDI investment, and nightlight intensity (as a proxy for economic development). Findings from previous studies on the relationship between FDI and air pollution are inconclusive with some evidence of the deleterious consequences for the environment (e.g., Shahbaz, Nasreen, Abbas, & Anis, 2015). On one hand, pollution-intensive industries likely move from richer to poorer economies because environmental rules and regulations in the latter are relatively weaker. On the other hand, other studies indicate that FDI can contribute to a cleaner environment, especially if it comes with green technologies (e.g., Demena & Afesorgbor, 2020). The results presented in Panels A, B, and C of Table B11 show that locations with lower levels of industrial production record more reduced air pollution after the lockdown. We also conduct a similar exercise focusing on agricultural activities. Farming activities have been recognized as one of air pollution sources which stems from fertilized fields and livestock waste. It is thus reasonable to expect that provinces with less agricultural production witness more decreased air pollution. The results in Panel D of Table B11 confirm our expectation.

We also examine whether citizen perceptions about the environment in Vietnam affect the impacts of the COVID-19-induced lockdown on air pollution. We obtain data from the PAPI database which provides indicators of quality of local economic governance. We are interested in two dimensions—that is, seriousness in environmental protection and quality of air—both of which are available at the province level. The estimation results, shown in Table B12, provide evidence that locations where citizens have higher awareness about the environment do not witness more improved air quality up to four weeks after the lockdown date. The improvements in air quality in these locations appear to occur only eight weeks after the lockdown date.

Does our analytical framework to estimate the impacts of the lockdowns on air quality generalize to other countries beyond Vietnam? One challenge with cross-country analysis is that not all countries have a single official lockdown date, and if they do, not all countries cleanly implement the lockdowns for the whole country. As such, we compile a list of 67 countries which we are able to identify the national lockdown date from reliable sources (such as reputable media sources or local government websites). These lockdown dates range from March 9, 2020 (Italy) to April 7, 2020 (Singapore) and are shown in Figure B1 and Table B13 together with their sources. As with Vietnam, we also put together a database on concentration of NO_2 for these 67 countries for analysis. The estimation results, shown in Table B14, point to similar negative impacts of the lockdowns on reduced air pollution. In terms of magnitude, our cross-country estimates are comparable to those found by Dang and Trinh (2021) using a sample of 164 countries, but are relatively smaller than those obtained for Vietnam (Table 1). A possible explanation is that Vietnam had a more successful lockdown with stronger compliance by its population (Jennings, 2020), which in turn determines the changes in air pollution.

We further extend our analysis to study the impacts of the second lockdown in Vietnam on air quality. After 99 days of no community transmission, the outbreak came back in the last week of July 2020 in the coastal city of Da Nang and spread to other provinces (Dinh, 2020). The government quickly responded by reimposing broader restrictions nationwide and implementing partial lockdowns in four provinces until the last week of September (Ewers & Schmitz, 2020).[6] It is demonstrated by an increase in the stringency index as shown in Figure A2, although the increase is less than the national lockdown in April. We thus examine whether the second lockdown still affects air quality using a subsample of areas under the second lockdown. We present the results in Table B15 using a similar RDiT framework, which show consistent impacts of the lockdown on air pollution, with the effect magnitudes being comparable to those in Table 1.

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[6] Areas in the second lockdown in Vietnam are Da Nang city, Quang Nam, Hai Duong and Dak Lak.

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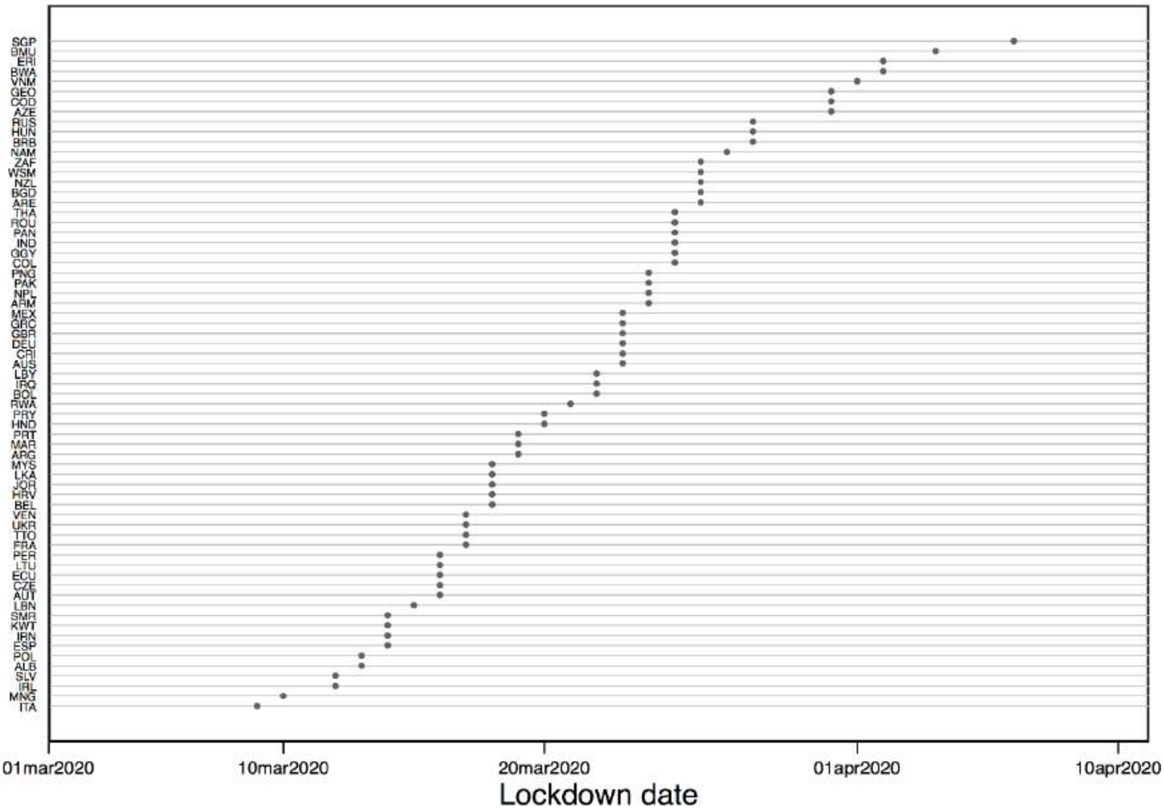
Figure B1: Lockdown dates by country



Notes: We collect the underlying data on the lockdown dates from reliable sources including the media and local governments, which are provided in Table B13.

Table B1: Data sources and summary statistics

Variable	Descriptions	Mean	Standard deviation	Min	Max
Satellite air quality (daily)					
Source: European Union's Copernicus programme (https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-5p)					
NO_2	Nitrogen dioxide	24.962	21.571	-12.100	427.000
CO	Carbon Monoxide	0.049	0.015	0.018	0.856
SO_2	Sulphur Dioxide	-0.021	2.194	-9.480	33.600
O_3	Ozone	11.976	0.530	10.832	13.421
Satellite weather data (daily)					
Source: National Oceanic and Atmospheric Administration (NOAA) (https://www.ncep.noaa.gov)					
Rainfall	Average rainfall (m)	0.002	0.004	0.000	0.030
Temperature	Average temperature (K)	298.069	4.363	281.834	308.665
Google Mobility data					
Source: Google Community Mobility Reports (https://www.google.com/covid19/mobility/)					
Retail & Recreation	Changes in people's mobility (percent) in different categories	-25.690	18.445	-84.000	32.000
Grocery & pharmacy		-13.780	17.411	-66.000	53.000
Park		-21.801	18.728	-80.000	74.000
Transit		-25.034	22.910	-81.000	94.000
Workplaces		-1.450	18.493	-71.000	62.000
Residential		8.029	5.386	-8.000	35.000
Apple Mobility data					
Source: Apple Mobility Reports (https://covid19.apple.com/mobility)					
Driving	Volume of directions requests per city (Hanoi and Ho Chi Minh City) compared to a baseline volume on 13 January 2020.	81.291	21.579	23.420	120.990
Walking		84.442	23.280	28.220	134.310
Flight data					
Source: Airports Corporation of Vietnam (https://www.vietnamairport.vn/en/)					

Number of flights	Number of daily domestic and international flights	125.758	187.443	0.000	1,590.000
Oxford COVID-19 Government Response Tracker (OxCGRT)					
Source: Blavatnik School of Government at the University of Oxford (https://covidtracker.bsg.ox.ac.uk/)					
Stringency index	Government responses to COVID-19 (Score between 0 and 100)	60.913	18.356	28.700	96.300
Government response index		56.084	16.718	22.440	85.900
Containment and health index		64.420	18.081	26.520	96.970
Economic support index		10.246	12.295	0.000	25.000
Other control variables (Tables B11 and B12)					
Industrial index	Province growth rate of industrial production (Statistical Yearbook 2019)	113.055	12.683	99.400	188.500
FDI	Foreign direct investment projects licensed by province (Statistical Yearbook 2019)	7,068.502	11,296.800	1.500	45,194.300
Nightlight	Average night-time light at the district level in 2019 (National Oceanic and Atmospheric Administration – NOAA)	3.362	9.922	0.103	148.763
Agricultural production	Total production of rice in thousand tons (Statistical Yearbook 2019)	755.632	918.286	28.200	4,285.900
Environmental protection	Viet Nam Provincial Governance and Public Administration Performance Index (PAPI) in 2019	3.559	0.528	2.710	4.940
Quality of air		1.935	0.198	1.290	2.430

Notes: Summary statistics of real-time data are calculated using the bandwidth of eight weeks before and after the lockdown date.

Table B2: COVID-19 lockdowns and air pollution – Optimal bandwidth

Air pollution:	Optimal bandwidth		
NO_2	Imbens and Kalyanaraman	CCT (Calonico, Cattaneo, and Titiunik)	Cross-valid (Lee and Lemieux)
Lockdown=1	-5.808***	-4.740***	-3.826***
	(0.443)	(0.423)	(0.410)
Optimal bandwidth	[-16, 16]	[-29, 16]	[-21, 21]
Means before lockdowns	24.441	24.441	24.441
Controls	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	3,518	6,280	6,417

Notes: *** p<0.01, ** p<0.05, * p<0.1. Results of RDD using the optimal bandwidths based on Imbens and Kalyanaraman (2012), Calonico et al. (2014) and Lee and Lemieux (2010). Clustered standard errors in parentheses are robust to within-day and within-district serial correlation. Mean of air quality before lockdowns is calculated two weeks before the official date of lockdown. All regressions include province dummies and month dummies. Control variables are daily temperature and precipitation.

Table B3: Placebo test

	Time prior to lockdown date				
Air quality:	1 week	2 weeks	3 weeks	4 weeks	1 year
NO_2	(1)	(2)	(3)	(4)	(5)
Lockdown=1	-0.502	-1.145*	-0.881	1.222	0.255
	(0.823)	(0.689)	(0.858)	(0.837)	(0.681)
Means before lockdowns	24.441	24.441	24.441	24.441	24.441
Controls	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes
Observations	9,516	10,409	11,522	12,798	11,087

Notes: *** p<0.01, ** p<0.05, * p<0.1. Results of RDD. Clustered standard errors in parentheses are robust to within-day and within-district serial correlation. Mean of air quality before lockdowns is calculated two weeks before the official date of lockdown. Control variables are daily temperature and rainfall.

Table B4: COVID-19 lockdowns and air pollution – "Donut" RDD

	Excluding observations near the lockdown date in		
Air quality:	+/-1 week	+/-2 weeks	+/-3 weeks
NO_2	(1)	(2)	(3)
Lockdown=1	-2.318*	-6.980***	-7.692***
	(1.355)	(1.438)	(1.611)
Means before lockdowns	25.369	25.369	25.369
Controls	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	21,578	19,333	16,434

Notes: *** p<0.01, ** p<0.05, * p<0.1. Results of "Donut" RDD using the bandwidth of +/-8 weeks from the lockdown date. Clustered standard errors in parentheses are robust to within-day and within-district serial correlation. Air pollution is measured by NO_2 from satellite data. Running variable is number of days from the lockdown date. The model includes interactions of running variable (linear and quadratic terms) with treatment variable. All regressions include province dummies and month dummies. Control variables are daily temperature and precipitation.

Table B5: COVID-19 lockdowns and air pollution – Lagged dependent variable estimation

Air quality:	(1)	(2)	(3)
NO_2	+/-2 week	+/-4 weeks	+/-8 weeks
Lockdown=1	-4.252***	-4.238***	-7.788***
	(0.849)	(0.735)	(1.297)
Lagged dependent variable	0.525***	0.412***	0.532***
	(0.052)	(0.042)	(0.037)
Means before lockdowns	24.441	27.579	25.369
Controls	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	673	3,274	11,191

Notes: *** p<0.01, ** p<0.05, * p<0.1. Results of parametric RDD. Clustered standard errors in parentheses are robust to within-day and within-district serial correlation. Air pollution is measured by NO_2 from satellite data. Running variable is number of days from the lockdown date. The model includes interactions of running variable (linear and quadratic terms) with treatment variable. All regressions include province dummies and month dummies. Control variables are daily temperature and precipitation.

Table B6: Response indexes components

Number	Components	Description	Stringency index	Government response	Containment and health
1	School closing	Closings of schools and universities	x	x	x
2	Workplace closing	Closings of workplaces	x	x	x
3	Cancel public events	Cancelling public events	x	x	x
4	Restrictions on gatherings	Cut-off size for bans on private gatherings	x	x	x
5	Close public transport	Closing of public transport	x	x	x
6	Stay at home requirements	Orders to "shelter-in- place" and otherwise confine to home.	x	x	x
7	Restrictions on internal movement	Restrictions on internal movement	x	x	x
8	International travel controls	Restrictions on international travel	x	x	x
9	Income support	Salaries/cash payments to people who lose their jobs		x	
10	Debt relief	Government freezing financial obligations		x	
11	Public info campaigns	Presence of public info campaigns	x	x	x
12	Testing policy	Who can get tested?		x	x
13	Contact tracing	Governments doing contact tracing?		x	x

Notes: Each component is measured by an ordinal scale. The indexes are measured by the OxCGRT team as simple averages of the individual component indicators. Each component is measured by an ordinal scale (e.g., 0 – no measures, 1 – recommended closing, 2 – require partial closing, 3 – require closing all levels). It is then rescaled by maximum value to create a score between 0 and 100. These scores are then averaged to get the response indexes.

Table B7: COVID-19 lockdowns and air pollution – Fuzzy RDD

Air pollution:	(1)	(2)	(3)
NO_2	Stringency index	Government response index	Containment and health index
Lockdown=1	-8.450***	-3.777***	-2.633***
	(1.696)	(0.566)	(0.700)
Means before lockdowns	24.441	24.441	24.441
Controls	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	64,679	64,679	64,679

Notes: *** p<0.01, ** p<0.05, * p<0.1. Results of fuzzy RDD. The running variable is response indexes taken from OxCGRT data. Clustered standard errors in parentheses are robust to within-day and within-district serial correlation. Air pollution is measured by NO_2 from satellite data. Mean of air quality before lockdowns is calculated two weeks before the official date of lockdown. All regressions include province and day dummies. Control variables are daily temperature and precipitation.

Table B8: COVID-19 lockdowns and air pollution – Air pollution in log

Air quality:	+/-2 weeks		+/-4 weeks		+/-8 weeks	
NO_2 (in log)	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Linear model						
Lockdown=1	-0.322***	-0.306***	-0.206***	-0.216***	-0.168***	-0.217***
	(0.021)	(0.021)	(0.018)	(0.017)	(0.034)	(0.034)
Panel B: Linear interaction model						
Lockdown=1	-0.302***	-0.272***	-0.205***	-0.214***	-0.171***	-0.218***
	(0.021)	(0.021)	(0.018)	(0.017)	(0.034)	(0.034)
Panel C: Quadratic model						
Lockdown=1	-0.330***	-0.321***	-0.204***	-0.211***	-0.168***	-0.217***
	(0.021)	(0.021)	(0.018)	(0.017)	(0.034)	(0.034)
Panel D: Quadratic interaction model						
Lockdown=1	-0.394***	-0.406***	-0.202***	-0.205***	-0.170***	-0.219***
	(0.027)	(0.027)	(0.018)	(0.018)	(0.034)	(0.034)
Means before lockdowns	3.099	3.099	3.159	3.159	3.047	3.047
Controls	No	Yes	No	Yes	No	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,524	3,518	8,636	8,620	22,962	22,851

Notes: *** p<0.01, ** p<0.05, * p<0.1. Results of parametric RDD. Clustered standard errors in parentheses are robust to within-day and within-district serial correlation. Air pollution is measured by NO_2 from satellite data. Running variable is number of days from the lockdown date. Model 1 uses running variable in linear form, Model 2 includes interaction of running variable and treatment variable, Model 3 includes quadratic term of running variable, Model 4 includes interactions of running variable (linear and quadratic terms) with treatment variable. All regressions include province dummies and month dummies. Control variables are daily temperature and precipitation.

Table B9: COVID-19 lockdowns and air pollution – Province linear time trend

Air quality:	+/-2 weeks		+/-4 weeks		+/-8 weeks	
NO_2	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Linear model						
Lockdown=1	-19.626***	-10.112***	-14.946***	-11.861***	-8.586***	-12.301***
	(1.923)	(2.092)	(2.159)	(2.057)	(1.903)	(1.994)
Panel B: Linear interaction model						
Lockdown=1	-21.418***	-16.481***	-14.985***	-11.899***	-8.500***	-12.309***
	(1.919)	(2.117)	(2.128)	(2.028)	(1.899)	(1.997)
Panel C: Quadratic model						
Lockdown=1	-23.192***	-18.920***	-15.037***	-11.934***	-8.490***	-12.319***
	(1.930)	(2.158)	(2.119)	(2.020)	(1.900)	(1.999)
Panel D: Quadratic interaction model						
Lockdown=1	-27.256***	-20.886***	-15.090***	-11.950***	-8.493***	-12.296***
	(2.113)	(2.291)	(2.127)	(2.027)	(1.900)	(1.996)
Means before lockdowns	24.441	24.441	27.579	27.579	25.369	25.369
Controls	No	Yes	No	Yes	No	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Province linear time trend	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,524	3,518	8,636	8,620	22,962	22,851

Notes: *** p<0.01, ** p<0.05, * p<0.1. Results of parametric RDD. Clustered standard errors in parentheses are robust to within-day and within-district serial correlation. Air pollution is measured by NO_2 from satellite data. Running variable is number of days from the lockdown date. Model 1 uses running variable in linear form, Model 2 includes interaction of running variable and treatment variable, Model 3 includes quadratic term of running variable, Model 4 includes interactions of running variable (linear and quadratic terms) with treatment variable. All regressions include province dummies and month dummies. Control variables are daily temperature and precipitation.

Table B10: COVID-19 lockdowns and air pollution – Power-stations and cement plants (capacity)

Air pollution: NO_2	(1) +/-2 weeks	(2) +/-4 weeks	(3) +/-8 weeks
Panel A: Coal-fired plants			
Lockdown* Non-coal plants	-1.228***	-1.359***	-1.242***
	(0.432)	(0.380)	(0.240)
Panel B: Cement plants			
Lockdown* Non-cement plants	-1.367***	-0.177	-0.436***
	(0.272)	(0.214)	(0.132)
Controls	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	3,518	8,620	22,851

Notes: *** p<0.01, ** p<0.05, * p<0.1. Results of parametric RDD that includes interactions of running variable (linear and quadratic terms) with treatment variable. Clustered standard errors in parentheses are robust to within-day and within-district serial correlation. All regressions include region dummies and month dummies. Control variables are daily temperature and precipitation.

Table B11: COVID-19 lockdowns and air pollution – Industrial production indicators

Air pollution:	(1)	(2)	(3)
NO_2	+/-2 weeks	+/-4 weeks	+/-8 weeks
Panel A: Industrial production index			
Lockdown*Industrial index	-21.698**	-4.196	0.288
	(9.257)	(6.303)	(3.849)
Observations	3,518	8,620	22,851
Panel B: FDI capital			
Lockdown* FDI (in log)	-0.344*	-0.198	-0.348***
	(0.197)	(0.145)	(0.102)
Observations	3,518	8,620	22,851
Panel C: Nightlight			
Lockdown*Nightlight	-0.718**	-0.512*	-0.477**
	(0.326)	(0.295)	(0.186)
Observations	3,439	8,399	22,246
Panel D: Agricultural production			
Lockdown*Agricultural production	-10.466***	-5.591***	-7.432***
	(2.149)	(1.920)	(1.236)
Observations	3,518	8,620	22,851
Controls	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes

Notes: *** $p<0.01$, ** $p<0.05$, * $p<0.1$. For ease of interpretation, industrial (agricultural) production indicators are reversed so that higher index indicates less industrial (agricultural) activities. Results of parametric RDD that includes interactions of running variable (linear and quadratic terms) with treatment variable. Clustered standard errors in parentheses are robust to within-day and within-district serial correlation. Air pollution is measured by NO_2 from satellite data. All regressions include province and month dummies. Control variables are daily temperature and precipitation.

Table B12: COVID-19 lockdowns and air pollution – Citizens perception

Air pollution:	(1)	(2)	(3)
NO_2	+/-2 weeks	+/-4 weeks	+/-8 weeks
Panel A: Environmental protection			
Lockdown*Environmental protection	-1.041	1.386	-4.033***
	(1.645)	(1.171)	(0.672)
Panel B: Quality of air			
Lockdown*Quality of air	-9.535	3.545	-10.229***
	(7.659)	(5.106)	(2.868)
Controls	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	3,518	8,620	22,851

Notes: *** p<0.01, ** p<0.05, * p<0.1. Results of parametric RDD that includes interactions of running variable (linear and quadratic terms) with treatment variable. Clustered standard errors in parentheses are robust to within-day and within-district serial correlation. Air pollution is measured by NO_2 from satellite data. All regressions include month dummies. Control variables are daily temperature and precipitation. A higher score on PAPI indexes is associated with better awareness of environmental protection and quality of air, respectively.

Table B13: National lockdown date by country

Number	Country	Country code	Official lockdown date	Source
1	Albania	ALB	3/13/20	https://www.reuters.com/article/us-health-coronavirus-albania/albania-extends-lockdown-till-end-of-coronavirus-outbreak-idUSKBN21J6AZ
2	Argentina	ARG	3/19/20	https://www.bloomberg.com/news/articles/2020-03-20/argentina-orders-exceptional-lockdown-in-bid-to-contain-virus
3	Armenia	ARM	3/24/20	https://www.reuters.com/article/health-coronavirus-armenia/update-1-armenia-closes-down-enterprises-bans-outdoor-movements-without-passport-pm-idUSL8N2BH7AW
4	Australia	AUS	3/23/20	https://www.abc.net.au/news/2020-03-22/major-coronavirus-crackdown-to-close-churches-pubs-clubs/12079610
5	Austria	AUT	3/16/20	https://www.businessinsider.com/how-austria-reacted-quickly-and-firmly-to-tackle-coronavirus-crisis-2020-4?r=AU&IR=T
6	Azerbaijan	AZE	3/31/20	https://www.aa.com.tr/en/latest-on-coronavirus-outbreak/azerbaijan-to-impose-curfew-amid-coronavirus-outbreak/1785680
7	Bangladesh	BGD	3/26/20	https://thediplomat.com/2020/04/the-covid-19-catastrophe-in-bangladesh/
8	Barbados	BRB	3/28/20	https://www.voice-online.co.uk/news/coronavirus/2020/03/27/barbados-to-impose-nightly-curfews-as-covid-cases-jump-to-24/
9	Belgium	BEL	3/18/20	https://www.usnews.com/news/world/articles/2020-03-17/belgium-to-impose-coronavirus-lockdown-from-march-18-at-1100-gmt
10	Bermuda	BMU	4/4/20	https://www.garda.com/crisis24/news-alerts/328696/bermuda-government-announces-24-hour-curfew-from-april-4-update-1
11	Bolivia	BOL	3/22/20	https://www.reuters.com/article/us-health-coronavirus-bolivia/bolivia-announces-nationwide-14-day-quarantine-to-stem-spread-of-coronavirus-idUSKBN2180VG
12	Botswana	BWA	4/2/20	https://www.osac.gov/Content/Report/f5897d81-7dfa-42eb-a614-1854dd818775
13	Colombia	COL	3/25/20	https://www.reuters.com/article/us-health-coronavirus-colombia-quarantin/colombia-to-hold-19-day-quarantine-to-fight-coronavirus-idUSKBN218068
14	Republic of Congo	COD	3/31/20	https://www.msn.com/en-xl/news/other/covid-19-lagos-brazzaville-lockdown-begins/ar-BB11ZAhn
15	Costa Rica	CRI	3/23/20	https://www.ministeriodesalud.go.cr/index.php/centro-de-prensa/noticias/741-noticias-2020/1582-gobierno-endurece-medidas-sanitarias-para-impedir-contagio-de-covid-19
16	Croatia	HRV	3/18/20	https://www.total-croatia-news.com/news/42223-covid-19

17	Czech Republic	CZE	3/16/20	https://orf.at/stories/3158055/
18	Ecuador	ECU	3/16/20	https://www.garda.com/crisis24/news-alerts/322931/ecuador-government-to-close-all-borders-due-to-covid-19-march-15-16-update-1
19	El Salvador	SLV	3/12/20	https://www.theguardian.com/world/live/2020/mar/11/coronavirus-update-live-news-uk-health-minister-italy-lockdown-australia-us-china-stock-markets-outbreak-latest-updates?page=with:block-5e6971ab8f085f0b8d946d20#block-5e6971ab8f085f0b8d946d20
20	Eritrea	ERI	4/2/20	https://www.garda.com/crisis24/news-alerts/328486/eritrea-authorities-implement-21-day-lockdown-from-april-2-update-3
21	France	FRA	3/17/20	https://www.independent.co.uk/news/world/europe/coronavirus-france-lockdown-cases-update-covid-19-macron-a9405136.html
22	Georgia	GEO	3/31/20	https://www.nytimes.com/2020/04/04/us/coronavirus-georgia-beaches.html
23	Germany	DEU	3/23/20	https://www.cnbc.com/2020/04/16/germany-set-to-lift-lockdown-cautiously-while-uk-exit-strategy-remains-unknown.html
24	Greece	GRC	3/23/20	https://www.reuters.com/article/us-health-coronavirus-greece-curfew/greece-imposes-lockdown-after-coronavirus-infections-jump-idUSKBN2190Z1
25	Guernsey	GGY	3/25/20	https://guernseypress.com/news/2020/03/24/coronavirus-guernsey-in-lockdown-from-midnight-tonight/
26	Honduras	HND	3/20/20	https://covid19honduras.org/?q=toque-de-queda-absoluto-para-todo-el-pais
27	Hungary	HUN	3/28/20	https://www.usnews.com/news/world/articles/2020-03-27/hungary-to-restrict-people-leaving-their-homes-to-fight-coronavirus-pm
28	India	IND	3/25/20	https://www.nytimes.com/2020/03/24/world/asia/india-coronavirus-lockdown.html
29	Iran	IRN	3/14/20	https://www.garda.com/crisis24/news-alerts/322811/iran-natiowide-lockdown-implemented-as-over-11300-covid-19-cases-confirmed-march-13-update-12
30	Iraq	IRQ	3/22/20	https://www.garda.com/crisis24/news-alerts/325526/iraq-nationwide-lockdown-implemented-march-22-update-15
31	Ireland	IRL	3/12/20	https://www.theguardian.com/world/2020/mar/27/stay-home-varadkar-urges-irish-in-drastic-lockdown
32	Italy	ITA	3/9/20	https://www.bbc.com/news/world-europe-51810673
33	Jordan	JOR	3/18/20	https://www.abc.net.au/news/2020-05-07/how-jordan-is-tackling-coronavirus/12188520
34	Kuwait	KWT	3/14/20	https://www.algemeiner.com/2020/03/13/preparing-for-coronavirus-lockdown-kuwait-asks-muslims-to-pray-at-home/
35	Lebanon	LBN	3/15/20	https://www.france24.com/en/20200315-lebanon-announces-two-week-lockdown-over-coronavirus

36	Libya	LBY	3/22/20	https://www.libyanexpress.com/libya-on-lockdown-from-6-00-pm-to-6-00-am-amid-coronavirus-preventive-measures/
37	Lithuania	LTU	3/16/20	https://www.garda.com/crisis24/news-alerts/324497/lithuania-government-closes-borders-to-foreign-nationals-march-16-update-2
38	Malaysia	MYS	3/18/20	https://www.todayonline.com/world/covid-19-malaysia-goes-nationwide-pause-march-18-and-what-we-know-so-far
39	Mexico	MEX	3/23/20	https://medicalxpress.com/news/2020-06-mexico-reopening-two-month-lockdown.html
40	Mongolia	MNG	3/10/20	https://www.garda.com/crisis24/news-alerts/321181/mongolia-government-places-ulaanbaatar-and-other-cities-on-lockdown-due-to-covid-19-march-10-update-7
41	Morocco	MAR	3/20/20	https://www.reuters.com/article/us-health-coronavirus-morocco/morocco-to-ease-coronavirus-lockdown-measures-idUSKBN23G2ZH
42	Namibia	NAM	3/27/20	https://www.usnews.com/news/world/articles/2020-03-24/namibia-announces-travel-ban-partial-lockdown-after-seventh-coronavirus-case
43	Nepal	NPL	3/24/20	https://www.garda.com/crisis24/news-alerts/326601/nepal-government-announces-nationwide-lockdown-from-march-24-31-update-4
44	New Zealand	NZL	3/26/20	https://www.bbc.com/news/av/world-52001578
45	Pakistan	PAK	3/24/20	https://www.aa.com.tr/en/asia-pacific/pakistan-stays-under-lockdown-amid-coronavirus-outbreak/1777394
46	Panama	PAN	3/25/20	https://medicalxpress.com/news/2020-03-panama-lockdown-paraguay-borders.html
47	Papua New Guinea	PNG	3/24/20	https://www.businessadvantagepng.com/png-in-lockdown-what-it-means-for-you-and-your-business/
48	Paraguay	PRY	3/20/20	https://www.aa.com.tr/en/americas/paraguay-extends-lockdown-until-april-12-amid-virus/1783353
49	Peru	PER	3/16/20	https://www.bbc.com/news/world-latin-america-53150808
50	Poland	POL	3/13/20	https://www.bloomberg.com/news/articles/2020-03-13/poland-imposes-full-border-controls-quarantines-for-visitors
51	Portugal	PRT	3/19/20	https://www.usnews.com/news/world/articles/2020-03-19/portugal-restricts-movement-to-stem-coronavirus-rules-out-rationing
52	Romania	ROU	3/25/20	https://www.reuters.com/article/health-coronavirus-romania/romania-to-enforce-strict-lockdown-to-slow-coronavirus-idUSL8N2BH4LL
53	Russia	RUS	3/28/20	https://www.bbc.com/news/world-europe-52061381
54	Rwanda	RWA	3/21/20	https://www.dw.com/en/coronavirus-rwanda-imposes-africas-first-lockdown/a-52878787
55	Samoa	WSM	3/26/20	https://www.rnz.co.nz/international/pacific-news/412647/samoa-officially-on-lock-down

56	San Marino	SMR	3/14/20	https://www.sanmarinortv.sm/news/politica-c2/nuovo-decreto-legge-in-vigore-fino-al-6-aprile-a185082
57	Singapore	SGP	4/7/20	https://www.straitstimes.com/politics/ban-on-social-gatherings-of-any-size-in-homes-or-public-areas
58	South Africa	ZAF	3/26/20	https://www.washingtonpost.com/world/africa/south-africa-enters-lockdown-as-known-covid-19-cases-surpass-1000/2020/03/27/d6092194-6f7d-11ea-a156-0048b62cdb51_story.html
59	Spain	ESP	3/14/20	https://www.cnbc.com/2020/03/14/spain-declares-state-of-emergency-due-to-coronavirus.html
60	Sri Lanka	LKA	3/18/20	https://edition.cnn.com/world/live-news/coronavirus-outbreak-03-18-20-intl-hnk/h_865d45b4069a33a409d20daff4adee7b
61	Thailand	THA	3/25/20	https://www.straitstimes.com/asia/se-asia/thailand-declares-state-of-emergency-to-curb-spread
62	Trinidad and Tobago	TTO	3/17/20	https://www.nationnews.com/nationnews/news/244418/trinidad-lockdown
63	Ukraine	UKR	3/17/20	https://www.ukrinform.net/rubric-society/2899162-ten-facts-about-coronavirus-lockdown-in-ukraine.html
64	United Arab Emirates	ARE	3/26/20	https://www.forbes.com/sites/jamesasquith/2020/04/05/dubai-enters-24-hour-lockdown-as-travel-restrictions-extended-in-uae/#7a26ea44f312
65	United Kingdom	GBR	3/23/20	https://www.bbc.com/news/uk-53141763
66	Venezuela	VEN	3/17/20	https://www.reuters.com/article/us-health-coronavirus-venezuela-reopenin/some-venezuelans-welcome-relaxing-of-lockdown-after-14-weeks-inside-idUSKBN23O373
67	Vietnam	VNM	4/1/20	https://www.cnbc.com/2020/07/23/vietnam-zero-coronavirus-deaths.html

Table B14: COVID-19 lockdowns and air pollution – Cross-country sample

Air pollution:	(1)	(2)	(3)
NO_2	+/-2 weeks	+/-4 weeks	+/-8 weeks
Lockdown=1	-0.569	-0.945**	-1.391***
	(0.508)	(0.394)	(0.296)
Means before lockdowns	20.195	21.311	22.010
Controls	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	23,966	45,816	91,296

Notes: *** p<0.01, ** p<0.05, * p<0.1. Results of parametric RDD that includes interactions of running variable (linear and quadratic terms) with treatment variable. Clustered standard errors in parentheses are robust to within-day and within-district serial correlation. Air pollution is measured by NO_2 from satellite data. All regressions include country dummies and month dummies. Control variables are daily temperature and precipitation. We present summary of country lockdown dates in Figure B1.

Table B15: COVID-19 lockdowns and air pollution – Impacts of the second lockdown

Air pollution:	(1)	(2)	(3)
NO_2	+/-4 weeks	+/-8 weeks	+/-12 weeks
Lockdown=1	-4.433**	-5.048***	-3.144*
	(2.083)	(1.760)	(1.684)
Means before lockdowns	18.470	20.318	20.586
Controls	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	153	277	395

Notes: *** p<0.01, ** p<0.05, * p<0.1. Results of parametric RDD that includes interactions of running variable (linear and quadratic terms) with treatment variable. Clustered standard errors in parentheses are robust to within-day and within-district serial correlation. Control variables are daily precipitation. All regressions include province dummies and month dummies.