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Ambient air pollution is a major problem in many countries of the developing world. This study examines the relationship between long-term exposure to air pollution and COVID-19-related deaths in four countries of Latin America that have been highly affected by the pandemic: Brazil, Chile, Colombia, and Mexico. Relying on historical satellite-based measures of fine particulate matter concentrations and official vital statistics, our results suggest that an increase in long-term exposure of 1 Î¼g/m3 of fine particles is associated with a 2.7 percent increase in the COVID-19 mortality rate. This relationship is found primarily in municipalities of metropolitan areas, where urban air pollution sources dominate, and air quality guidelines are usually exceeded. Our findings support the call for strengthening environmental policies that improve air quality in the region, as well as allocating more health care capacity and resources to those areas most affected by air pollution.

Keywords: air pollution, COVID-19, Latin America, long-term

JEL Codes: I18, C10, I14, Q53

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Abstract

Ambient air pollution is a major problem in many countries of the developing world. This study examines the relationship between long-term exposure to air pollution and COVID-19-related deaths in four countries of Latin America that have been highly affected by the pandemic: Brazil, Chile, Colombia, and Mexico. Relying on historical satellite-based measures of fine particulate matter concentrations and official vital statistics, our results suggest that an increase in long-term exposure of 1 μg/m^3 of fine particles is associated with a 2.7 percent increase in the COVID-19 mortality rate. This relationship is found primarily in municipalities of metropolitan areas, where urban air pollution sources dominate, and air quality guidelines are usually exceeded. Our findings support the call for strengthening environmental policies that improve air quality in the region, as well as allocating more health care capacity and resources to those areas most affected by air pollution.

Keywords: COVID-19, SARS-CoV-2, coronavirus, air pollution, particulate matter, Latin America.

JEL Classification: I18, Q52, Q53, O54, O13

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1 Introduction

Ambient air pollution poses a significant threat to human health as it is linked to millions of deaths every year (World Bank, 2016; World Health Organization, 2016a). Previous studies show that exposure to poor air quality is associated with lower respiratory infections, chronic obstructive pulmonary disease, ischemic heart disease, and strokes, among others (Institute for Health Metrics and Evaluation, 2018). By weakening the immune system, long-term exposure to air pollution may also affect the physiological response against new diseases, such as COVID-19 (e.g., Frontera et al. (2020); Benmarhnia (2020)). In this paper, we explore this link by looking at long-term air pollution exposure and deadly outcomes from COVID-19 in the context of Latin America.

Latin American countries often lack strong institutions to successfully control and promote air pollution abatement. Unsurprisingly, air pollution has become the biggest environmental hazard in Latin America (World Health Organization, 2016b), where only four out of fifty seven cities that monitor fine particulate matter ($PM_{2.5}$) concentrations meet World Health Organization (WHO)'s guidelines (Riojas-Rodríguez et al., 2016). Indeed, recent $PM_{2.5}$ records in Bogota, Mexico City, Santiago, and Sao Paulo show that concentrations are more than six times above WHO's recommended standard (see Appendix Figure B1), which leaves more than 33 million people in the region at risk.[1] Furthermore, the regions is characterized by high rates of informality and health systems with limited and unequal capacity (OECD, 2020). The costs of exposure to air pollution may substantially increase when they are coupled with weak environmental institutions (Tanaka, 2015), and limited health care capacity (Guidetti et al., 2021). In addition, inequality is prevalent in the region and an important fraction of its population lives in poverty, all of these further exacerbates the adverse effects of poor air quality (Rose-Pérez, 2015; Lome-Hurtado et al., 2020).

Latin America has been severely affected by the coronavirus pandemic. Health systems throughout the region reached critical levels and hospitals became short of capacity during peak periods. Several countries followed a set of stringent policies to address the spread of coronavirus, with many cities imposing lock-downs and stay-at-home orders sending millions of people to confinement. Despite these efforts, the region experienced one of the highest mortality rates in the world. In fact, whereas Latin America's total population represents only 8.4 percent of the global population, the total number of deaths from COVID-19 stands at roughly 1.3 million (Lancet, 2021), which is equivalent to almost 30 percent of the fatalities worldwide. The extent to which these deadly outcomes has been affected by the historically

[1] The WHO guideline for yearly average concentrations of fine particulate matter ($PM_{2.5}$) is currently set at 10 $\mu g/m^3$.

elevated levels of air pollution in the region remains yet unknown.

We examine the relationship between long-term air pollution exposure and deadly outcomes from COVID-19 by focusing on Brazil, Chile, Colombia, and Mexico, countries with the highest mortality rates in the region.[2] The analysis relies on municipality-level satellite data of average $PM_{2.5}$ concentrations from 2000 to 2018. We combine this data with official statistics on municipal-level COVID-19 confirmed fatalities during 2020. Throughout our estimations, we take into account socioeconomic and health characteristics, as well as potential country- and state-specific unobservable effects that may, otherwise, act as confounders.

Our results show a positive and significant link between long-term $PM_{2.5}$ exposure and COVID-19 mortality in both a pooled sample as well as in country-specific analyses. This relationship turns stronger for municipalities that are located in metropolitan areas, which usually exceed the WHO air quality guidelines. Our findings for these areas suggest that a 1 $\mu g/m^3$ increase in long-term $PM_{2.5}$ average exposure is associated with a 2.7 percent increase in the COVID-19 mortality rate. Country-specific analyses suggest that this association may be even higher for metropolitan areas of countries such as Brazil.

While several studies provide evidence of the link between long-term air pollution and COVID-19 mortality, most of them use data from developed countries. For example, Wu et al. (2020) find a positive association in the United States, whereas Cole et al. (2020) and Coker et al. (2020) provide similar evidence for the Netherlands and northern Italy, respectively.[3] Among the studies for developing countries, Zheng et al. (2021) find a positive association between long-term exposure to $PM_{2.5}$, PM_{10}, and NO_2, and the risk and severity of COVID-19 infection in China. Meanwhile, Yamada et al. (2021) find that districts of India severely affected $PM_{2.5}$ concentrations experience significant increases in COVID-19 deaths and fatality rates, whereas López-Feldman et al. (2021) show similar evidence for the metropolitan area of Mexico City.[4] We add to this literature by exploring the link between long-term air pollution exposure and COVID-19 mortality for a comprehensive set of countries in Latin America, which share similar characteristics and face common socioeconomic and environmental challenges. Moreover, Latin America still faces one of the highest levels of income inequality in the world, which poses additional challenges to reduce the threat of both air pollution and COVID-19 equally across the region. By focusing the

[2]According to the Johns Hopkins University's Coronavirus Resource Center, Brazil has experienced thus far 265.15 fatalities per hundred thousand people, Colombia 241.75, Mexico 190.12, and Chile 188.22. Data retrieved from `https://coronavirus.jhu.edu/data/mortality`, accessed on July 2021.

[3]Similar studies explore the link between COVID-19 fatalities and other pollutants. See for instance, Konstantinoudis et al. (2021); Travaglio et al. (2021); Ogen (2020) and Perone (2021).

[4]Other related studies are Bolaño-Ortiz et al. (2020) that explore the relationship between long-term exposure to pollution and the spread of coronavirus in Latin America, and Rodriguez-Villamizar et al. (2021) that looks at air pollution exposure and COVID-19 mortality in Colombia.

analysis on Latin America, we provide a first glimpse of the role of air pollution as a risk factor of COVID-19 mortality within such a context.

2 Materials and Methods

2.1 Data

COVID-19 Mortality. Data on mortality comes from each country's official statistics. The National Institute of Health and the Ministry of Health, for Colombia and Mexico, respectively, register individual-level deaths per day. In Brazil, individual-level data comes from the Ministry of Health's surveillance system for Severe Acute Respiratory Syndrome (SARS) cases. For Chile, however, patient-level information is not publicly available. Through the Ministry of Science, the Ministry of Health releases the number of confirmed COVID-19 fatalities, although aggregated at the municipality level. Thus, for consistency of our analysis, we aggregate individual data per municipality for Brazil, Colombia, and Mexico. Our final measure of mortality is the total number of COVID-19-confirmed deaths per municipality in each country during 2020.[5]

Table 1: Descriptive Statistics on 2020 COVID-19 Mortality by Country

Country	Mean	Std. Dev.	Min.	Max.	Obs.
Panel A. Number of Deaths					
Brazil	34.925	326.204	0	15,679	5,550
Chile	49.606	103.743	0	811	345
Colombia	39.402	335.883	0	9,960	1,119
Mexico	61.933	254.58	0	3,903	2,297
Panel B. Mortality Rate					
Brazil	0.609	0.464	0	3.309	5,550
Chile	0.581	0.514	0	2.495	345
Colombia	0.385	0.359	0	2.299	1,119
Mexico	0.620	0.617	0	11.091	2,297

Notes: This table shows the main descriptive statistics on the 2020 COVID-19 number of deaths and mortality rate by country. Observations are at the municipality level. Panel A shows the number of COVID-19 deaths averaged across municipalities from January 1st to December 31st, 2020. Panel B shows the COVID-19 mortality rate (per 1,000 people) during 2020. Data were retrieved on January 2021.

Descriptive statistics on the number of COVID-19 fatalities and mortality rates are presented in Table 1 for the countries in our sample. The total number of deaths during 2020

[5]The data that we use is official data which has been validated by the authorities from each country and is therefore the best publicly available data. Furthermore, by using country and state fixed effects in our empirical estimations we capture, at least partially, the potential measurement error that can be present across and within countries.

differs in order of magnitude across countries. Fatalities were roughly 17,000 in Chile and 44,000 in Colombia, while they reached 142,000 in Mexico and almost 194,000 in Brazil. Panel A of Table 1 shows that municipality-level average fatality ranges between 35 and 62 deaths across countries. Moreover, Panel B shows that Colombia and Mexico present the lowest and highest average municipality-level mortality rate, with 0.39 and 0.62 deaths per 1,000 people, respectively. Standard deviations indicate variation in fatalities across municipalities within each country, with some experiencing no deaths during 2020.

Pollution Satellite Imagery. Uniform and comprehensive sources of air quality across countries are rare. Ground-level monitoring stations are generally available only for large cities in each country, and their coverage over time generally differs between them. This situation prevents us from using air concentrations from monitoring stations. Instead, we employ satellite imagery as a measure of particle air pollution. Although satellite-based information may be subject to criticism because of its wide spatial resolution, it has the advantage of allowing us access to homogeneous records of air pollution concentrations for all municipalities in our analysis and across several years. We obtain long-term average annual concentrations of fine particulate matter ($PM_{2.5}$) from Hammer et al. (2020). This data is available at 0.01×0.01 degrees ($\approx 1.1 \times 1.1$ km) from 1998 to 2018. From this dataset, we create a long-term municipality-averaged measure of air pollution by computing the mean of $PM_{2.5}$ for grid-cells within each municipality and year, from 2000 to 2018. We also compute $PM_{2.5}$ averages for the period 2010-2018 to be used later in a robustness analysis.[6] Country maps of $PM_{2.5}$ levels and mortality rates at the municipal level are shown in Figure 1.

Table 2: Descriptives Statistics on 2000-2018 Fine Particulate Matter ($PM_{2.5}$) Concentrations

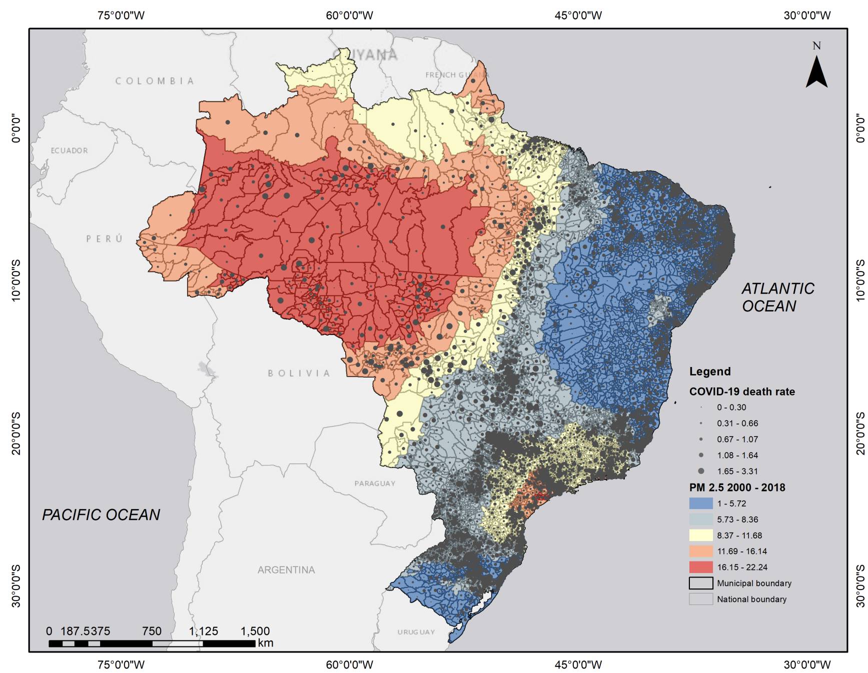
Country	Mean	Std. Dev.	Min.	Max.	Obs.
Brazil	7.39	3.37	3.21	22.24	5,547
Chile	8.23	4.91	1.25	20.67	345
Colombia	23.18	6.51	8.56	38.36	1,119
Mexico	12.96	4.33	4.93	29.11	2,297

Notes: This table shows main descriptive statistics on average annual $PM_{2.5}$ pollution concentrations by country. Pollution is measured in $\mu g/m^3$. Observations are at the municipality level. Annual concentrations averaged from 2000 to 2018. Data correspond to long-term trends of fine particulate matter concentrations obtained from Hammer et al. (2020).

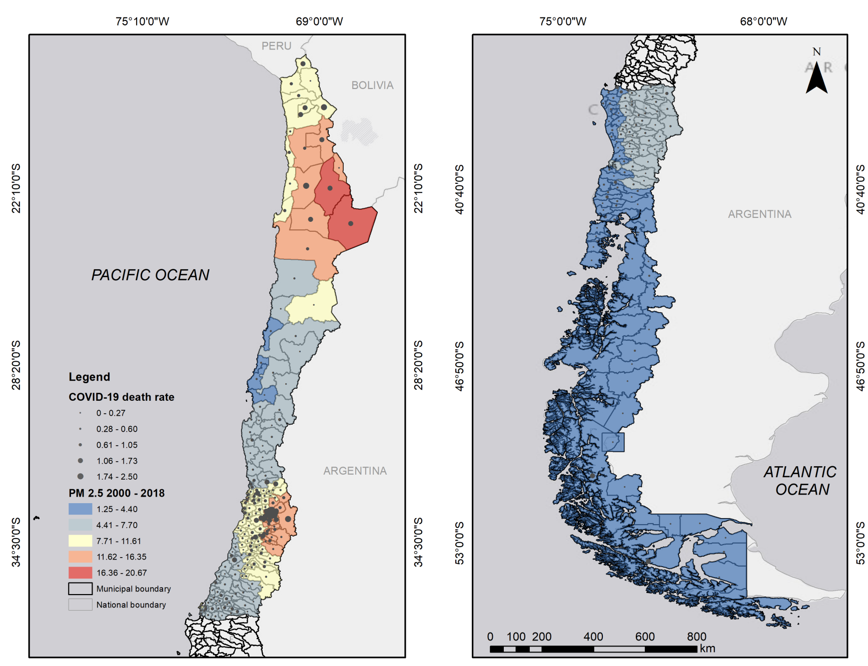
Table 2 displays descriptive statistics of fine particle concentrations averaged from 2000

[6] For Colombia, we exclude two municipalities (*San Andres* and *Providencia*) because of lack of $PM_{2.5}$ data.

to 2018 (averages for 2010-2018 are shown in Appendix Table B1). We can observe that while several municipalities exceed the annual WHO Air Quality Guideline of 10 $\mu g/m^3$, there is also a substantial variation in air pollution within and across countries. For instance, some

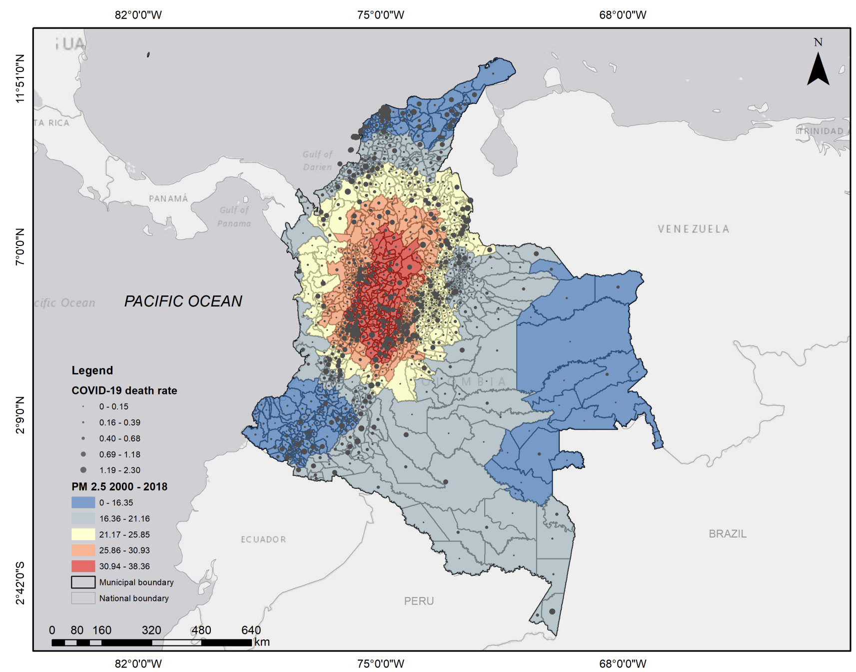


(a) Brazil

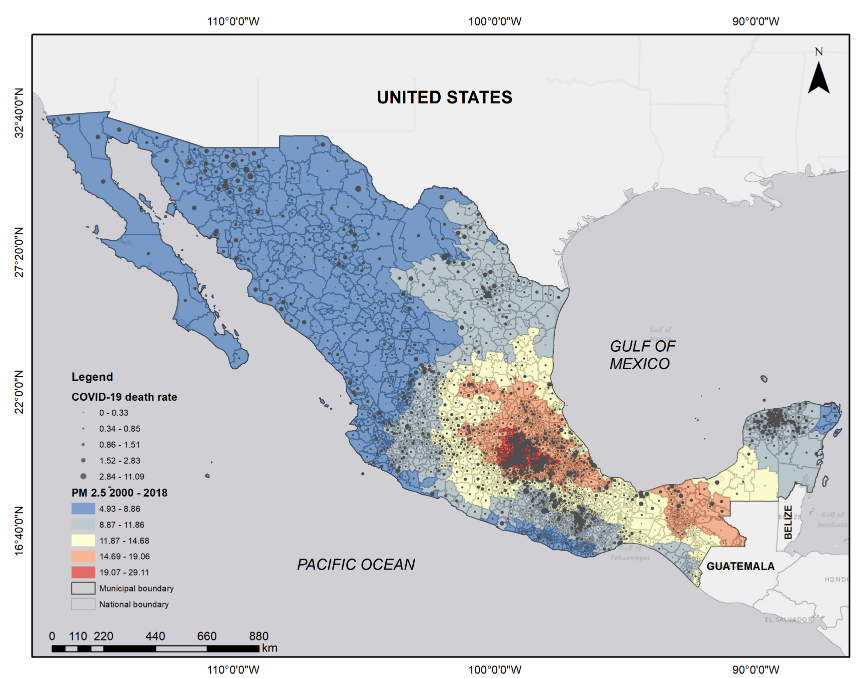


(b) Chile

Continue on the next page



(c) Colombia



(d) Mexico

Figure 1: Distribution of Long-Term Pollution ($PM_{2.5}$) Concentrations and COVID-19 Deaths in Latin America

Notes: This figure shows the spatial distribution of long-term fine particulate matter ($PM_{2.5}$) concentrations, averaged from 2000 to 2018, and 2020 COVID-19 mortality rate per 1,000 people across municipalities of selected countries in Latin America. We measure pollution in $\mu g/m^3$, and the data correspond to long-term trends of $PM_{2.5}$ concentrations obtained from Hammer et al. (2020). Data on municipality-level COVID-19 mortality rates come from each country's official sources for 2020.

municipalities in Colombia exhibit maximum annual average $PM_{2.5}$ concentrations that are above 38 μg/m^3, while some Chilean municipalities display average concentrations as low as 1.25 μg/m^3. Average pollution exposure is the highest in Colombia, while Brazil exhibits the lowest level. These statistics remain practically unchanged when we only consider the period 2010-2018 (see Appendix Table 2), which suggests the lack of substantial air quality improvements in these countries over time.

To get a better sense of the link between COVID-19 fatalities and long-term air pollution, Figure 2 depicts the relationship between mortality rate and the satellite-based long-term average $PM_{2.5}$ concentrations using the entire sample of municipalities across all four countries. We split this relation into metropolitan (right-hand side) and non-metropolitan (left-hand side) areas.[7] For a better exposition, we overlay a linear prediction plot and its 95%-significance confidence interval. Whereas there seems to be no clear relationship between mortality rate and long-term annual $PM_{2.5}$ concentrations in municipalities of non-metropolitan areas, we observe that for localities within metropolitan areas, there is a positive correlation between these two variables. Due to this contrast, we distinguish between metro and non-metro areas in all our estimations in Section 3.

Covariates. We merge death counts per municipality with $PM_{2.5}$ data and other municipality-level variables in each country. We include several covariates in our estimations to account for possible confounders that may also affect mortality. Doing so, we get an estimate of the link between air pollution and COVID-19 deaths that is statistically isolated from the influence of other factors. These variables account for demographics, socioeconomic characteristics, and health conditions. Although ideally we would like to consider the same covariates for the four countries, this is not possible due to data availability. Therefore, throughout all our estimations, we use two groups of variables: (i) a common set of covariates available for the four countries (hereafter called the "common-set"); and (ii) a richer set of covariates that, in addition to those variables included in (i), includes variables available for each country (hereafter called the "richer-set").

Common-Set of Covariates. It comprises a set of eight common covariates available for the four countries. It includes the proportion of people in different age ranges (15-44, 45-64, above 65), to take into account the possibility that COVID-19 deaths may concentrate in the older groups of the population. Population density (number of inhabitants per square kilometer in each municipality) is included to allow for differences in the probability of

[7]The metropolitan area classification is based on criteria established by each country. See Appendix A for detailed information.

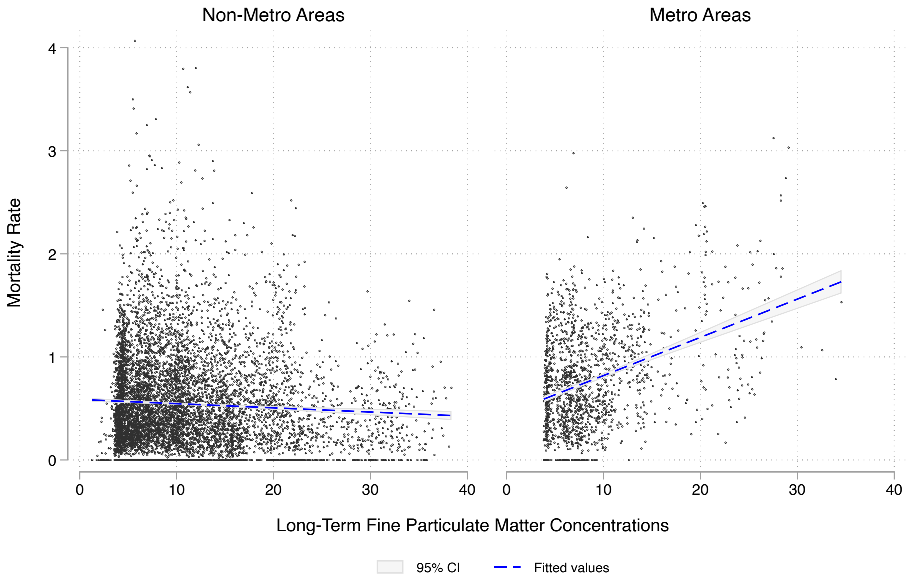


Figure 2: COVID-19 Mortality Rate and Long-Term $PM_{2.5}$ Concentrations in Latin American Municipalities

Notes: This figure shows the relationship between COVID-19 mortality rate and long-term average $PM_{2.5}$ concentrations across Latin American municipalities within metropolitan and non-metropolitan areas. The dashed blue line represents a linear prediction with confidence intervals obtained at the 95% significance (shaded areas). The mortality rate is per 1,000 people. Pollution is measured in $\mu g/m^3$. Data on mortality rates come from the sources mentioned in Section 2. Data on pollution concentrations are long-term trends of fine particulate matter concentrations obtained from Hammer et al. (2020).

transmission across municipalities. Socioeconomic variables include the proportion of adults that did not finish high school and the proportion of inhabitants that live in rurality. These variables aim to allow for variation in development levels across localities. Finally, we include two health-related variables: the number of hospital beds and the number of days since the first COVID-19 case was detected in each municipality. The pandemic strongly challenged the operation and capacity of existing healthcare systems. An overly stressed healthcare system may affect the timing in which a COVID-19 patient receives medical treatment, and thus increase the risk of death. The number of hospital beds, therefore, informs us on the healthcare capacity available, and indirectly on the preparedness of healthcare systems to face this unprecedented crisis. Lastly, the number of days since the first COVID-19 case inform us about variation across localities in the length of exposure to the SARS-CoV-2 virus.

Richer-Set of Covariates. It includes the common set of covariates as well as country-specific variables that may affect the risk of COVID-19-related death. The additional covariates are poverty rate, the Gini coefficient, the proportion of minority and non-minority population, the proportion of people with pre-existing conditions (such as diabetes, hypertension, obesity, and respiratory diseases), the proportion of overcrowding, and access to health services, among others (see Table A1 in the Appendix for the complete list of covariates for each country).

2.2 Methods

Our study examines the relationship between long-term air pollution exposure and the COVID-19 mortality rate in a selected group of Latin American countries.Similar to Wu et al. (2020), we estimate a linear specification of the relationship between the number of deaths and long-term ambient $PM_{2.5}$ concentrations. To do so, we use a pooled cross-section model of municipalities for four countries: Brazil, Chile, Colombia, and Mexico. We estimate the following equation:

$$ln\, E[Deaths_{ij}] = \beta_0 + \beta_1 Pollution_{ij} + \mathbf{X_{ij}}\gamma + Country_j + ln\,(Population_{ij}) + \epsilon_{ij}, \qquad (1)$$

where $Deaths_{ij}$ refers to the cumulative number of deaths in municipality i in country j during 2020; $Pollution_{ij}$ is the 2000-2018 satellite-based average of $PM_{2.5}$ concentrations in municipality i in country j; $Country_j$ is a fixed effect by country; $Population_{ij}$ is municipality i's population; and ϵ_{ij} is an error term. The vector $\mathbf{X_{ij}}$ includes a set of covariates that affect the risk of mortality and are available for the four countries at the municipality level (see the common-set of covariates in Section 2).

In addition to the pooled Equation 1, we also conduct estimations separately for each country. By doing this, we estimate heterogeneous coefficients regarding the association between air pollution and COVID-19 mortality rates across countries. Furthermore, apart from the covariates used in Equation (1), we include variables that are only available to some countries (see the richer-set of covariates in Section 2). The equation to estimate is as follows:

$$ln\, E[Deaths_i^j] = \beta_0^j + \beta_1^j Pollution_i^j + \mathbf{Z_i}^j\gamma^j + State_i + ln\,(Population_i)^j + \epsilon_i^j, \qquad (2)$$

where the elements of the equation are defined as above, except for $State_i$ that now represents a state-level fixed effect, and the vector $\mathbf{Z_i}^j$ that includes the common-set of variables as well as country-specific covariates (i.e., the richer-set).[8]

[8] In the case of Colombia, when the sample is restricted to metropolitan areas the low number of munici-

Our interest in Equations (1) and (2) is to estimate β_1 and β_1^j, which would reflect the statistical effect of long-term air pollution as a predictor of the number of COVID-19 fatalities in each municipality i, for the pooled sample and in each country, respectively. We estimate Equations (1) and (2) using a maximum likelihood estimator assuming a Poisson distribution and restricting the coefficient of the population size to one. We impose this restriction to estimate the relationship between changes in pollution exposure and mortality rates instead of the number of fatalities. Based on the estimates for β_1 and β_1^j, we report incidence rate ratios (IRR), which allows us to interpret estimated changes in mortality as the relative risk of being exposed to increased pollution.

3 Results

In section 3.1 we show results for the relationship between long-term $PM_{2.5}$ pollution exposure and COVID-19 mortality rates in Latin America by pooling all municipalities together. Then, in the subsequent subsection, we allow for a heterogeneous relationship between pollution exposure and deaths by estimating country-specific results.

3.1 Pooled Sample

Table 3 presents parameter estimates for the relationship between long-term exposure to $PM_{2.5}$ and COVID-19 mortality rates across Latin American municipalities. Panel A shows the result using the full sample of municipalities, while Panel B and C show estimation results for municipalities within metropolitan and non-metropolitan areas, respectively. For each set of municipalities, columns exhibit estimation results providing alternative ways of including additional covariates; column (3) represents the specification with the largest available set of controls.

Starting with Panel A of Table 3, the results in column (1) indicate a strong and positive relationship between long-term exposure to $PM_{2.5}$ and fatalities associated with COVID-19. In particular, we observe that one additional microgram per cubic meter of $PM_{2.5}$ is associated with a 1.6 percent increase in the mortality rate associated with the coronavirus disease. This effect remains positive, although it lacks statistical significance after controlling for additional factors that may also affect our outcome variable (column (2)), and when unobservable factors common to each country are taken into account (column (3)). Notwithstanding, this result holds positive and turns statistically significant when we look at this

palities prevents the use of state-fixed effects in the regressions. Instead, we include a fixed effect for Andean cities. Cities in high altitude tend to share similar socioeconomic and development dynamics, for instance, they are closer to coffee regions.

Table 3: Long-Term Average $PM_{2.5}$ Exposure and COVID-19 Mortality Rate in Latin American Municipalities

	(1)	(2)	(3)
Panel A. All Municipalities			
$PM_{2.5}$	1.016^{**}	1.004	1.008
	[1.002, 1.030]	[0.995, 1.013]	[0.996, 1.020]
Obs.	9,235	9,235	9,235
Panel B. Metropolitan Areas			
$PM_{2.5}$	1.019^{***}	1.015^{***}	1.027^{***}
	[1.007, 1.032]	[1.004, 1.026]	[1.014, 1.040]
Obs.	1,587	1,587	1,587
Panel C. Non-Metropolitan Areas			
$PM_{2.5}$	0.998	1.005	1.001
	[0.984, 1.011]	[0.995, 1.014]	[0.988, 1.013]
Obs.	7,648	7,648	7,648
Common-Set of Controls		×	×
Country Fixed Effects			×

Notes: This table shows regression estimates of COVID-19 mortality rates on annual $PM_{2.5}$ concentrations averaged from 2000 to 2018. Estimates shown are incidence rate ratios from Poisson regressions offsetting by population and clustering standard errors at the state level. Observations are municipalities. Common-set includes explanatory variables as defined in Section 2. Brackets show 95% confidence intervals. Significance levels: $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

relationship within Latin American municipalities that belong to metropolitan areas in Panel B, and even after including additional covariates in the estimation equation (columns (2) and (3)). Results shown in column (2) of Panel B show that one additional unit of $PM_{2.5}$ increases the mortality rate associated with the COVID-19 disease by 1.5 percent in municipalities belonging to metropolitan areas. This result is consistent with Figure 2, discussed earlier. This relationship increases in magnitude once we control for country-specific fixed effects, in column (3). The estimated incidence rate ratio in this column suggests that one additional microgram per cubic meter of $PM_{2.5}$ increases the COVID-19 mortality rate by 2.7 percent for those municipalities in metropolitan areas.

Regarding municipalities in non-metropolitan areas, the results in Panel C show no statistically significant association between long-term average $PM_{2.5}$ concentrations and mortality rate due to the coronavirus. Taken together, these results suggests that the likelihood of an increased risk of dying from COVID-19 due to long-term exposure to ambient air pollution is significant only in metropolitan areas of Latin America.

3.2 Country-Specific Results

The link between long-term $PM_{2.5}$ air pollution and COVID-19 deaths in each country is depicted in Table 4. Panel I shows results for Brazil, Panel II for Chile, and Panel III and IV for Colombia and Mexico, respectively. Columns (1) to (3) follow the same structure as in Table 3. This time, however, we add column (4), which depicts the results of estimating Equation (2) using the richer set of covariates as defined in Section 2. For each country, we present results for all municipalities in Panel A, and municipalities in metropolitan and non-metropolitan areas in Panels B and C.

3.2.1 Brazil

The results for Brazil in Panel I of Table 4 show a positive relationship between long-term exposure to $PM_{2.5}$ pollution and COVID-19 mortality rates, which is in line with the results presented in Table 3 for the four Latin American countries as a whole. In particular, the results in column (1) of Panel A using the full sample of Brazilian municipalities show that one additional unit of $PM_{2.5}$ is significantly associated with a 5.1 percent increase in mortality rate due to COVID-19. This result remains statistically significant, but it decreases in magnitude once we consider other factors that may affect COVID-19 deaths, as observed in columns (2) and (3). When we control for the entire set of potentially related factors available for Brazil that may affect our outcome variable, the result from column (4) shows that an additional unit of $PM_{2.5}$ is associated with a 2 percent increase in COVID-19 mortality rates. However, this result is no longer statistically significant.

The positive association between long-term pollution and COVID-19 mortality found for all Brazilian municipalities holds invariably when we consider only those localities within metropolitan areas in Panel B. This time, however, this association remains statistically significant regardless of the number of additional covariates that we control for in our estimation equation. More specifically, results from our preferred specification in column (4) suggests that one additional microgram of $PM_{2.5}$ pollution is associated with a 5 percent increase in mortality rate due to COVID-19. When contrasting this result with the one found for all metropolitan localities of Latin American in Table 3, we observe that the deadly COVID-19 effects of pollution exposure are, on average, more critical in metropolitan areas of Brazil than in similar municipalities of other countries of the region.[9]

[9] In fact, 58 percent of the municipalities in metropolitan areas of Brazil that present long-term average $PM_{2.5}$ concentrations above the World Health Organization's air quality guideline are located within the state of Sao Paulo – the most highly urbanized region in Brazil, and home of the largest vehicle fleet in the country. To the extent that long-term exposure to harmful concentrations of other pollutants, such as carbon monoxide (CO) or nitrogen oxides (NO_X)—which in addition to $PM_{2.5}$ are commonly emitted by combustion engines of light-duty vehicles— is exacerbating the risk of death from COVID-19, then the estimate shown

On the other hand, the results for non-metropolitan areas, presented in Panel C, seem to suggest a reduced risk of mortality from exposure to $PM_{2.5}$ pollution. This is an unexpected finding which might be the result of something unique to Brazil. The country has been constantly suffering from a large number of wildfires that are increasingly affecting tropical forests, savannas, and wetlands, which are located in rural areas of the country (i.e., non-metropolitan areas). For instance, as shown in panel (a) of Figure 1, the highest levels of $PM_{2.5}$ are found in municipalities of the State of Mato Grosso, a state that concentrates almost 20 percent of all wildfire outbreaks detected in Brazil during 2000-2018.[10] At the same time, and likely due to their low population density levels, the COVID-19 mortality rate in these municipalities was less than half the mortality rate in non-rural localities of the country during 2020. This suggests that our specification may be failing at capturing pollution dynamics that are specific to rural areas. Future research relating $PM_{2.5}$ and COVID-19 fatalities could explore further into the different sources of air pollution across rural and non-rural areas, which would better guide actions for pollution abatement.

3.2.2 Chile

The positive relationship between long-term $PM_{2.5}$ exposure and COVID-19 fatalities is also observed in the results for Chile, presented in Panel II. The findings shown in Panel A indicate that one additional unit of $PM_{2.5}$ is associated with an increase in COVID-19 mortality rate in the order of 6 to 10 percent (columns (1)-(4)). In our preferred specification using the richer set of controls (column (4)), we observe that one additional unit of $PM_{2.5}$ is associated with a 6 percent increase in the mortality rate due to COVID-19.

This relationship is found positive and statistically significant for metropolitan areas as well, although it decreases in magnitude to a 2.6 percent in our preferred specification in column (4). Instead, for localities in non-metropolitan areas, we observe that this positive relationship becomes larger in magnitude and highly statistically significant. The results presented in column (4) of Panel C show that one additional unit of fine particulate matter is associated with an 8.6 percent increase in COVID-19 mortality rate. This finding is important because, unlike what is observed for other countries in the region, the results for non-metropolitan municipalities of Chile suggest that long-term exposure to fine particulate matter may be an important risk factor of dying from COVID-19 in localities that do not necessarily belong to highly urbanized areas. A plausible explanation for this result could

in column (4) may reflect the overall effect of long-term exposure to a wider range of pollutants instead of capturing an effect that is exclusive to $PM_{2.5}$ concentrations. Nonetheless, our estimate in column (4) gives us a first glimpse of the potential association between long-term exposure to harmful air pollution in general and the risk of death from COVID-19.

[10] Source: National Institute for Space Research (INPE)'s website, accessed on August 2021.

Table 4: Long-Term Average $PM_{2.5}$ Exposure and COVID-19 Mortality Rate by Country

	(1)	(2)	(3)	(4)
Panel I. Brazil				
Panel A. All Municipalities				
$PM_{2.5}$	1.051***	1.020**	1.029**	1.020
	[1.027, 1.076]	[1.003, 1.039]	[1.001, 1.058]	[0.991, 1.051]
Obs.	5,547	5,515	5,514	5,513
Panel B. Metropolitan Areas				
$PM_{2.5}$	1.041***	1.021*	1.057***	1.050***
	[1.015, 1.068]	[1.000, 1.042]	[1.023, 1.091]	[1.018, 1.084]
Obs.	1,401	1,397	1,396	1,395
Panel C. Non-Metropolitan Areas				
$PM_{2.5}$	1.025**	1.010	0.971**	0.964**
	[1.006, 1.044]	[0.993, 1.027]	[0.945, 0.997]	[0.936, 0.993]
Obs.	4,146	4,118	4,118	4,118
Panel II. Chile				
Panel A. All Municipalities				
$PM_{2.5}$	1.097***	1.100***	1.070***	1.060***
	[1.083, 1.111]	[1.077, 1.125]	[1.018, 1.124]	[1.034, 1.086]
Obs.	346	324	324	321
Panel B. Metropolitan Areas				
$PM_{2.5}$	1.095***	1.088***	1.022	1.026**
	[1.078, 1.112]	[1.071, 1.106]	[0.988, 1.057]	[1.002, 1.050]
Obs.	64	64	64	62
Panel C. Non-Metropolitan Areas				
$PM_{2.5}$	1.099***	1.108***	1.105***	1.086***
	[1.048, 1.152]	[1.062, 1.155]	[1.039, 1.175]	[1.043, 1.131]
Obs.	281	260	260	259
Panel III. Colombia				
Panel A. All Municipalities				
$PM_{2.5}$	1.006	1.003	1.003	0.997
	[0.983, 1.030]	[0.989, 1.016]	[0.986, 1.020]	[0.978, 1.015]
Obs.	1,119	1,100	1,100	924
Panel B. Metropolitan Areas				
$PM_{2.5}$	1.003	1.009	1.019***	1.014***
	[0.991, 1.014]	[0.998, 1.020]	[1.006, 1.032]	[1.012, 1.015]
Obs.	22	22	22	22
Panel C. Non-Metropolitan Areas				
$PM_{2.5}$	1.001	0.994	1.008	0.999
	[0.977, 1.027]	[0.981, 1.007]	[0.984, 1.032]	[0.976, 1.024]
Obs.	1,097	1,078	1,078	902
Common-Set of Controls		×	×	
Richer-Set of Controls				×
State Fixed Effects			×	×

Continue on the next page

Table 4: Long-Term Average $PM_{2.5}$ Exposure and COVID-19 Mortality Rate by Country (cont.)

	(1)	(2)	(3)	(4)
Panel IV. Mexico				
Panel A. All Municipalities				
$PM_{2.5}$	1.024*	0.991	0.988	0.988
	[0.997, 1.052]	[0.978, 1.005]	[0.959, 1.017]	[0.966, 1.012]
Obs.	2,229	2,229	2,229	2,229
Panel B. Metropolitan Areas				
$PM_{2.5}$	1.042***	1.026***	1.020**	1.024***
	[1.016, 1.068]	[1.023, 1.029]	[1.003, 1.038]	[1.006, 1.042]
Obs.	104	104	104	104
Panel C. Non-Metropolitan Areas				
$PM_{2.5}$	0.977	1.002	1.004	0.997
	[0.949, 1.006]	[0.986, 1.018]	[0.977, 1.032]	[0.972, 1.024]
Obs.	2,125	2,125	2,125	2,125
Common-Set of Controls		×	×	
Richer-Set of Controls				×
State Fixed Effects			×	×

Notes: This table shows regression estimates of COVID-19 mortality rate on annual $PM_{2.5}$ concentrations averaged from 2000 to 2018. Estimates as incidence rate ratios from Poisson regressions offsetting by population and clustering standard errors at the state level. Results in columns (3) and (4) of Panel I exclude Brasilia. Results in columns (3) and (4) of Panel III (B) include an Andean-fixed effect instead of state-fixed effects. Brackets show 95% confidence intervals. Significance levels: $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

relate to the different sources of $PM_{2.5}$ emissions. Non-metropolitan municipalities of Chile are exposed to important sources of air pollution as well, which may differ from what is commonly known as the main sources of air pollution in metropolitan areas. For instance, mining activities and coal power generation is an important source of air pollution in non-metropolitan localities of northern Chile. Similarly, residential wood burning for heating is the main source of $PM_{2.5}$ in non-metropolitan localities of south-central and south Chile. Additionally, and unlike most countries in Latin America, Chile faces low temperatures during the winter period, which makes it more likely for the population of municipalities in non-metropolitan areas to be highly exposed to wood burning air pollution, at the same time that colder, and dry temperatures, constitute an additional risk factor for SARS-CoV-2 infection (Mandal and Panwar, 2020). This situation could particularly exacerbate the risk of death due to critical exposure to air pollution in Chilean municipalities that do not necessarily belong to metropolitan areas, relative to non-metropolitan municipalities of more tropical countries such as Brazil or Colombia. Unfortunately, our data prevents us from testing this hypothesis, which remains an open avenue for future research.

3.2.3 Colombia

The results for Colombia in Panel III hold consistently with the results previously observed for the whole region in Table 3. Overall, we observe a positive relationship between long-term $PM_{2.5}$ exposure and risk of death due to COVID-19 across all municipalities. Yet, these results lack statistical significance. Notwithstanding, when we restrict the sample to municipalities that are located in metropolitan areas only, we observe a positive and highly significant association, which is in line with the results for Brazil and Chile. In particular, using the common-set of covariates in column (3), we observe that one additional unit of $PM_{2.5}$ is associated with a 1.9 percent increase in the risk of death due to COVID-19. This result has a similar order of magnitude after taking into account additional factors that may also affect the mortality rate. In column (4), we observe an association of a 1.4 percent increase in the risk of COVID-19 death due to one extra unit of $PM_{2.5}$ concentration, which is lower than the estimated average for the four countries in Latin America. It is important to highlight that municipalities of metropolitan areas in Colombia are urban concentrations that include Bogota, Medellin – among others – with high levels of mobile source air pollution as in the case of Brazil. Pollution levels in these highly urbanized areas have induced authorities in Colombia to yearly announce $PM_{2.5}$-based air quality warnings to reduce exposure during periods of critical air pollution. In the case of non-metropolitan areas, however, we observe no significant relationship between $PM_{2.5}$ and COVID-19 fatalities.

3.2.4 Mexico

Finally, the results in Panel IV of Table 4 for Mexican municipalities tell a consonant story regarding long-term exposure to air pollution as a risk factor for COVID-19 mortality, particularly in metropolitan areas. Starting with all municipalities in Panel A, we observe a positive and statistically significant relationship of 2.4 percent in column (1). Yet, this significance is lost once we include stronger controls in our estimation equations.

Unsurprisingly, when we look at municipalities that are located in metropolitan areas (Panel B) we find positive and statistically strong relationships. The findings from our preferred specification, in column (4), suggest that the risk of death due to a coronavirus infection increases by 2.4 percent for an additional unit of exposure to fine particulate matter. The magnitude of this effect is similar to the results found for metropolitan municipalities in Chile (in Panel II) and the average effect found for all metropolitan localities in Panel B of Table 3.

3.3 Robustness Checks

The previous results consistently show a positive and statistically significant association between long-term average $PM_{2.5}$ exposure and COVID-19 mortality rate in metropolitan municipalities. Thus far, our definition of long-term exposure considers risk exposure to $PM_{2.5}$ pollution records averaged over 19 years, from 2000 to 2018. While this has been the standard for historical or long-term $PM_{2.5}$ pollution concentrations in the related literature (e.g., Wu et al. (2020); López-Feldman et al. (2021)), it is important to notice that policy-makers of several of the metropolitan areas under analysis undertook multiple actions and tighten environmental standards to curb air pollution concentrations during this period of time.[11] Hence, one possibility is that, as a result of these many efforts, or simply because of more awareness, exposure to fine particulate matter concentrations may have been lower during the more recent years. This would cause our previous results to overstate the risk of exposure to air pollution as a factor in the probability of dying from COVID-19. To account for this, we estimate Equations (1) and (2) using $PM_{2.5}$ concentrations for the period 2010 to 2018. This alternative test shows that our results remain unchanged when we use a more contemporaneous definition of long-term $PM_{2.5}$ pollution exposure (see Appendix Table B2 for the results for the pooled-sample of countries and Table B3 for the country-specific results).

In addition to a redefinition of our long-term pollution exposure measure, we also consider a distinction between municipalities that, in our sample, have been historically above or below the World Health Organization (WHO) air quality guideline of annual fine particulate matter concentrations. We do so as to classify cities with critical levels of long-term exposure to air pollution in a reliable and exogenous manner, and to explore whether our findings hold exclusively for these localities. To that end, we create an indicator variable that takes the value of one for municipalities with long-term average $PM_{2.5}$ concentrations equal or above 10 $\mu g/m^3$, and zero for municipalities below the guideline. By adding this indicator interacted with $PM_{2.5}$ in our estimations, we obtain an incidence rate ratio that is specific to cities above and below this guideline, allowing us to better compare the relationship between air pollution and COVID-19 mortality rate across cities with and without exposure to high levels of air pollution.

The results of this additional specification are shown in Appendix Table B4. For all municipalities in Panel A, we observe no statistically significant relationship between $PM_{2.5}$ and COVID-19 mortality, not even among localities with high levels of exposure to $PM_{2.5}$. Notwithstanding, when we consider only localities in metropolitan areas (Panel B), we ob-

[11] See for example Davis (2008); Gallego et al. (2013); Mullins and Bharadwaj (2015); Salvo and Wang (2017); Zhang et al. (2017); Bonilla (2019) and Rivera (2021).

serve that consistently throughout all three different specifications, there is a positive and significant association between $PM_{2.5}$ exposure and COVID-19 fatalities, which is specific to municipalities with pollution records historically above the WHO's air quality standard. We take the results in Table B4 as reassurance that long-term $PM_{2.5}$ exposure constitutes a notable risk factor in the probability of dying from COVID-19 in Latin American cities exposed to high levels of air pollution.

4 Discussion and Concluding Remarks

The ongoing pandemic caused by the spread of the novel coronavirus has resulted in more than 4 million deaths worldwide. More than 30 percent of these fatalities have taken place in Latin America, one of the regions hardest hit by this pandemic. Latin America is characterized by high and longstanding levels of poverty and inequality, lack of public health systems and health-care infrastructure, limited capability to follow quarantine and social distancing, and deficient access to social safety nets, which have all exacerbated the COVID-19 crisis in this region (e.g. Bolaño-Ortiz et al. (2020); Diez Roux et al. (2020); Henry (2020)). In this paper, we examine the role of an additional factor fueling this crisis; long-term exposure to harmful levels of air pollution.

Our findings are consistent with the notion that particle air pollution is linked to increased vulnerability, severe health outcomes, and fatal events due to COVID-19 (Frontera et al., 2020; Benmarhnia, 2020; López-Feldman et al., 2021; Coker et al., 2020; Cole et al., 2020; Perone, 2021; Wu et al., 2020). In particular, using municipality-level data for Brazil, Chile, Colombia, and Mexico, our results suggest that one additional unit of $PM_{2.5}$ pollution is associated with a 2.7 percent increase in the risk of dying from COVID-19 in metropolitan areas. This result is robust to several alternative specifications. Further analysis shows that this association holds only for municipalities of metropolitan areas that exceed WHO air quality guidelines. This would suggest that the adverse health effects of exposure to $PM_{2.5}$ on COVID-19 mortality are concentrated in urban areas that are exposed to high levels of air pollution over a long period of time.

Although not directly comparable, our findings are in line with previous estimates for other developing countries, such as those in Yamada et al. (2021), which find that one percent increase in long-term exposure to $PM_{2.5}$ ($\approx 2.46\ \mu g/m^3$) leads to a 0.027 percentage point increase in the mortality rate in India. For the case of Mexico, our results are slightly lower in magnitude relative to the estimates by López-Feldman et al. (2021), which use individual-level data for estimating the link between pollution exposure and COVID-19 mortality in the metropolitan area of Mexico City (MCMA). Nonetheless, our set of metropolitan municipalities includes localities in the Guadalajara's and Monterrey's conurbations in addition to those in the MCMA. Given that long-term average $PM_{2.5}$ concentrations recorded in these two metropolitan areas are roughly half the average concentrations found for the MCMA, it is reasonable to expect that estimates that include these localities will be attenuated towards zero relative to the findings for the MCMA alone. Finally, our results are different from Rodriguez-Villamizar et al. (2021), which find no statistically significant association between long-term exposure to $PM_{2.5}$ pollution and COVID-19 mortality for Colombia. While our data and methods differ from the ones in Rodriguez-Villamizar et al. (2021), it is highly plausible that our results differ due to the window of time for the mortality data: while Rodriguez-Villamizar et al. (2021) look at COVID-19 mortality up to July 17th, 2020, we use information for the whole year. Analysis of mortality data shows that roughly 50 percent of the Colombian municipalities reported their first COVID-19 case in August 2020 or later.

Our results are smaller relative to other studies looking at this relationship in the context of developed countries. For instance, Coker et al. (2020) find that an additional unit of long-term exposure to $PM_{2.5}$ pollution is associated with a 9 percent increase in COVID-19-related mortality for northern Italy, Cole et al. (2020) find a 13.6 percent increase for the Netherlands, and Wu et al. (2020) find an 8 percent increase for the United States. Our results may seem conservative relative to these studies as we pool together information from several countries, each one of them with distinct air pollution mitigation policies and varying strategies to control the pandemic. In our country-specific results, however, we obtain associations that are similar in magnitude to that of these previous findings, such as in the case of metropolitan areas of Brazil or non-metropolitan localities of Chile.

Our study has some limitations due to the characteristics of the data available. First, we use municipality-level data. While informative, our approach may obscure individual-level actions taken to avoid both coronavirus contagion and exposure to air pollution. Future research could delve deeper into the behavioral aspect of this relationship. Moreover, we use a homogeneous measure of pollution concentration within municipalities. If socioeconomically vulnerable individuals are less able to sort themselves towards low-pollution municipalities based on their preferences for air quality (or factors that closely correlate with it), and at the same time, they are more prone to develop a critical COVID-19 illness with deadly outcomes, then our results may be upward biased. Even though our results should not be considered as causal evidence of the relationship between pollution exposure and COVID-19 mortality rates, they provide strong evidence that a positive association exists. Exploiting variation in pollution exposure within municipalities, as well as an in-depth consideration of the multiple sources of endogeneity that may exist behind this link, remain as open avenues for future research.

Several other extensions of this paper are plausible. We could further look at the relationship between COVID-19 deaths and air pollutants other than $PM_{2.5}$, to better grasp the role of air pollution exposure as a risk factor in the COVID-19 mortality rate across non-metropolitan areas of Latin America. For instance, measures of other air pollutants could offer an alternative to exploring our research question in areas with a significant presence of extractive industries or increasing wildfires, as in the case of non-metropolitan municipalities of Chile and Brazil, respectively. Likewise, a more comprehensive model of air pollution that takes into account meteorological variables could capture potential atmospheric dynamics that may affect air pollution concentrations. Finally, understanding to which extent long-term exposure to air pollution detrimentally correlates with income inequality and poverty is crucial for adequate policy design in Latin America. Future research could explore whether the harmful effects of long-term air pollution exposure on COVID-19 fatalities change in magnitude across different segments of the income distribution in these countries.

The set of countries analyzed in this paper comprise a wide range of economies in Latin America, which offers variation in population size, geographic characteristics, and responses to the pandemic. Therefore, findings from this research are relevant for informing public health and environmental policy in the whole region. Our results provide compelling evidence that channeling additional health care capacity and resources to the most polluted areas could mitigate some of the adverse health effects of COVID-19. Moreover, our findings support the need for the strengthening of environmental policies aimed at reducing ambient air pollution in Latin America, which could alleviate some of the devastating and unequal effects of the coronavirus pandemic and, arguably, other pandemics that might arise in the future. Finally, while trying to control the COVID-19 pandemic and its aftermath, Latin American countries may be tempted to lessen environmental regulations in order to foster economic activity (López-Feldman et al., 2020). Our findings show that doing so could not only be detrimental for the control of the current pandemic, but it could also account for adverse responses to future disease threats.

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Appendix A. Data Sources

Definition of Metropolitan Areas. In Mexico, metropolitan areas are defined by the Ministry of Agrarian, Land and Urban Development (SEDATU), the National Population Council (CONAPO), and the National Institute of Statistics and Geography (INEGI); for this analysis we focus on metropolitan areas of at least 5 million inhabitants. In Chile, metropolitan areas are defined by the National Institute of Statistics (INE), while in Brazil by the Institute of Geography and Statistics (IBGE). In Colombia, however, there is no official classification of metropolitan areas, and thus, we use the functional urban area concept developed by the OECD (2020).

Table A1: Full List of Covariates

	Brazil	Chile	Colombia	Mexico
Panel A. Common-set:				
Number of days since first COVID-19 case	×	×	×	×
Number of hospital beds	×	×	×	×
Proportion of people between 15-44 years old	×	×	×	×
Proportion of people between 45-64 years old	×	×	×	×
Proportion of people 65 years old and older	×	×	×	×
Proportion of adults with less than high school	×	×	×	×
Proportion of rural population	×	×	×	×
Population density	×	×	×	×
Panel B. Richer-set:				
Gini coefficient		×		
Median household income	×	×		
Number of days since first at-home order		×		
Poverty rate or index	×	×	×	
Proportion of adults with less than elementary school		×		
Proportion of households owning a house	×	×		
Proportion of native or minority population	×	×		×
Proportion of population of African descent	×		×	×
Proportion of workers in the mining industry		×		
Proportion of households with low overcrowding		×		
Proportion of households with medium overcrowding		×		
Proportion of households with high overcrowding		×		
Proportion of people with public health insurance		×		
Proportion of people without healthcare access				×
Proportion of people with cardiovascular diseases	×			
Proportion of people with respiratory diseases	×	×	×	
Proportion of people with hypertension		×	×	
Proportion of people with diabetes (type II)	×	×	×	
Proportion of people with obesity			×	
Number of diabetes deaths per 100,000 population				×
Number of hypertension deaths per 100,000 population				×

Notes: The number of days since first COVID-19 case is the number of days since the first confirmed case in each country and December 31, 2020. The number of hospital beds is per 1,000 population. Population density is per km^2.

<u>Common-Set of Covariates.</u>

Brazil. Number of inhabitants, percentage of people for different age ranges (15-44, 45-64, and above 65), proportion of adults without high school and proportion of rural population come from the 2010 National Population Census (last available) collected by the Brazilian Institute of Geography and Statistics. Number of days since first COVID-19 case comes from the Ministry of Health. Number of hospital beds is the 2019 number of beds per 1,000 inhabitants computed at the state-level and obtained from the National Health Facilities Census (CNES), collected by the Ministry of Health.

Chile. Number of inhabitants, percentage of people for different age ranges (15-44, 45-64, and above 65), proportion of adults without high school and proportion of rural population come from the 2017 National Socioeconomic Characterization Survey (CASEN), a country-wide household survey with representation at the municipality-level. Number of days since first COVID-19 case comes from the Ministry of Health, through the Ministry of Science. This variable may be censored as the Ministry of Health publicly released municipality-level information starting on March 30, 2020 (first COVID-19 case in Chile was confirmed on March 3, 2020). Number of hospital beds is the 2019 number of beds per 1,000 inhabitants computed at the state-level and obtained from the Department of Health Statistics and Information (DEIS), part of the Ministry of Health.

Colombia. Number of inhabitants, percentage of people by age ranges (15-44, 45-64, and above 65), and proportion of adults without high school, all come from the 2018 population census data reported by DANE. The number of hospital beds come from the Special Registration of Health Supply Service (REPS) during 2020. The number of days since first case is computed using the first day of symptoms. Proportion of inhabitants in rurality is calculated by CEDE for 2018.

Mexico. Number of inhabitants, percentage of people for different age ranges (15-44, 45-64, and above 65), and proportion of adults that did not finish high school were obtained from Mexico's 2020 Census of Population and Housing (INEGI, 2021). Number of beds per 1,000 inhabitants comes from INEGI for 2018. The number of days since first case is computed using the first day of symptoms according to data from the Ministry of Health. Proportion of rural population was calculated using information from the 2020 Census.

<u>Richer-Set of Covariates.</u>

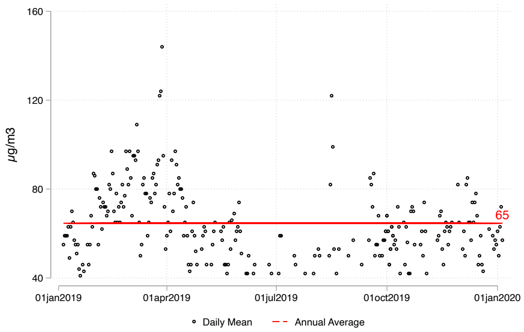
Brazil. Socioeconomic and demographic variables come from the 2010 Population Census. Proportion of black and indigenous residents in the municipality also come from the census. Number of diabetes- and hypertension-related deaths per 100,000 population is obtained from the 2019 Mortality Information System, collected by the Ministry of Health. Rural and urban classification comes from the 2017's Classification and characterization of rural and urban spaces in Brazil, published by IBGE.

Chile. All socioeconomic and demographic variables come from the 2017 National Socioeconomic Characterization Survey (CASEN). The Gini coefficient uses households' total income. Median household income is in 2017 USD. Number of days since first at-home order considers the first state-level at-home order (i.e., the first at-home order within the state, regardless of the municipality). Overcrowding is defined as the ratio between household members and the total number of bedrooms available to them. Low overcrowding is defined as between 2,5 and 3,49 members per bedroom. Medium overcrowding as between 3,5 and 4,9 members, while high overcrowding is more than 5 members per bedroom. Proportion of people with certain disease is self-reported information.

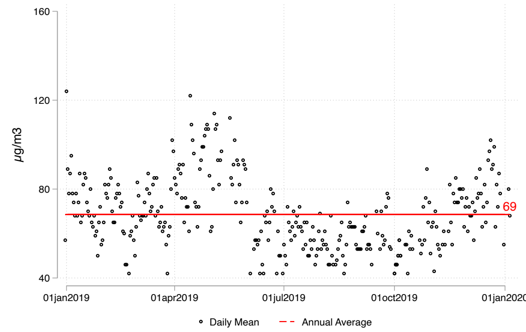
Colombia. Percentages of multidimensional poverty and of ethnicity (black) come from the 2018 population census reported by DANE. The proportion of peopled with diabetes, hypertension, respiratory diseases and obesity come from the Integrated System of Social Protection (SISPRO) in 2018.

Mexico. Proportion of natives, African descents, and proportion of population speaking an indigenous language all come from the 2021 INEGI. The proportion of people without healthcare access is also gathered from 2021 INEGI. Number of diabetes- and hypertension-related deaths per 100,000 population is obtained from the 2018 INEGI.

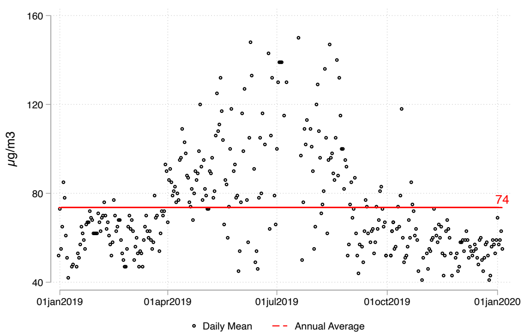
Appendix B. Additional Figures and Tables



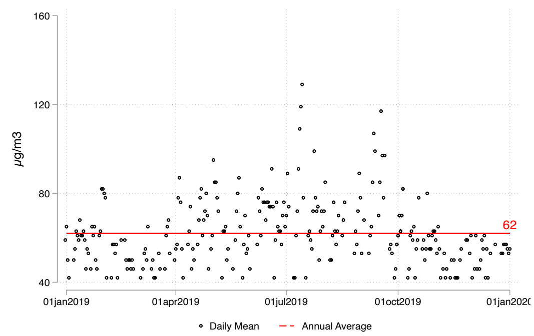
(a) Bogota



(b) Mexico City



(c) Santiago



(d) São Paulo

Figure B1: 2019 Daily $PM_{2.5}$ Concentrations in Major Metropolitan Cities of Latin America

Notes: This figure shows the 2019 daily median concentrations of ambient $PM_{2.5}$ in four metropolitan cities in Latin America. Scatters are daily medians averaged across multiple stations in each city after trimming the top and bottom 5%. Horizontal lines are annual averages. Data was obtained from the Air Quality Data Open Platform, retrieved on February 2021. Source: `aqicn.org/data-platform/covid19/`.

Table B1: Descriptive Statistics on 2010-2018 Average Fine Particulate Matter ($PM_{2.5}$) Concentrations

Country	Mean	Std. Dev.	Min.	Max.	Obs.
Brazil	7.62	3.15	3.36	21.02	5,547
Chile	8.88	5.08	1.19	21.65	345
Colombia	23.45	6.17	9.23	37.27	1,119
Mexico	12.13	3.74	4.84	25.99	2,297

Notes: This table shows main descriptive statistics on 2010-2018 averages of annual $PM_{2.5}$ pollution concentrations by country. Pollution is measured in $\mu g/m^3$. Observations are at the municipality level. Data correspond to long-term trends of fine particulate matter concentrations obtained from Hammer et al. (2020).

Table B2: 2010-2018 Average $PM_{2.5}$ Exposure and COVID-19 Mortality Rate in Latin American Municipalities

	(1)	(2)	(3)
Panel A. All Municipalities			
$PM_{2.5}$	1.015**	1.004	1.009
	[1.002, 1.029]	[0.994, 1.013]	[0.996, 1.022]
Obs.	9,235	9,235	9,235
Panel B. Metropolitan Areas			
$PM_{2.5}$	1.0197***	1.0131**	1.0283***
	[1.006, 1.034]	[1.002, 1.024]	[1.015, 1.041]
Obs.	1,587	1,587	1,587
Panel C. Non-Metropolitan Areas			
$PM_{2.5}$	0.995	1.004	1.000
	[0.981, 1.009]	[0.994, 1.014]	[0.987, 1.014]
Obs.	7,648	7,648	7,648
Common-Set of Controls		×	×
Country Fixed Effects			×

Notes: This table shows regression estimates of COVID-19 mortality rate on annual $PM_{2.5}$ concentrations averaged from 2010 to 2018. Results are estimates of incidence rates from Poisson regressions offsetting by population and clustering standard errors at the state level. Observations are municipalities. Common-set includes explanatory variables as defined in Section 2. Brackets show 95% confidence intervals. Significance levels: $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table B3: 2010-2018 Average $PM_{2.5}$ Exposure and COVID-19 Mortality Rate by Country

	(1)	(2)	(3)	(4)
Panel I. Brazil				
Panel A. All Municipalities				
$PM_{2.5}$	1.052***	1.017**	1.031**	1.083***
	[1.028, 1.077]	[1.000, 1.035]	[1.004, 1.059]	[1.030, 1.138]
Obs.	5,547	5,515	5,514	5,513
Panel B. Metropolitan Areas				
$PM_{2.5}$	1.039***	1.017*	1.056***	1.052***
	[1.014, 1.065]	[0.998, 1.038]	[1.022, 1.092]	[1.016, 1.088]
Obs.	1,401	1,397	1,396	1,395
Panel C. Non-Metropolitan Areas				
$PM_{2.5}$	1.024**	1.006	0.967**	0.959**
	[1.004, 1.045]	[0.988, 1.026]	[0.937, 0.998]	[0.926, 0.994]
Obs.	4,146	4,118	4,118	4,118
Panel II. Chile				
Panel A. All Municipalities				
$PM_{2.5}$	1.095***	1.096***	1.068***	1.059***
	[1.081, 1.110]	[1.073, 1.120]	[1.019, 1.120]	[1.033, 1.086]
Obs.	345	324	324	321
Panel B. Metropolitan Areas				
$PM_{2.5}$	1.094***	1.087***	1.024	1.025**
	[1.077, 1.111]	[1.069, 1.104]	[0.987, 1.062]	[1.000, 1.051]
Obs.	64	64	64	62
Panel C. Non-Metropolitan Areas				
$PM_{2.5}$	1.089***	1.097***	1.097***	1.078***
	[1.041, 1.139]	[1.054, 1.142]	[1.034, 1.165]	[1.036, 1.121]
Obs.	281	260	260	259
Panel III. Colombia				
Panel A. All Municipalities				
$PM_{2.5}$	1.010	1.007	1.005	0.998
	[0.983, 1.038]	[0.994, 1.021]	[0.989, 1.021]	[0.981, 1.015]
Obs.	1,119	1,100	1,100	924
Panel B. Metropolitan Areas				
$PM_{2.5}$	1.006*	1.027**	1.038***	1.023***
	[1.000, 1.011]	[1.004, 1.050]	[1.013, 1.063]	[1.022, 1.023]
Obs.	22	22	22	22
Panel C. Non-Metropolitan Areas				
$PM_{2.5}$	1.004	0.996	1.011	1.001
	[0.976, 1.032]	[0.980, 1.011]	[0.988, 1.034]	[0.979, 1.024]
Obs.	1,097	1,078	1,078	902
Common-Set of Controls		×	×	
Richer-Set of Controls				×
State Fixed Effects			×	×

Continue on the next page

Table B3: 2010-2018 Average $PM_{2.5}$ Exposure and COVID-19 Mortality Rate by Country (cont.)

	(1)	(2)	(3)	(4)
Panel IV. Mexico				
Panel A. All Municipalities				
$PM_{2.5}$	1.028^{*}	0.990	0.990	0.989
	[0.996, 1.060]	[0.974, 1.007]	[0.957, 1.023]	[0.962, 1.016]
Obs.	2,229	2,229	2,229	2,229
Panel B. Metropolitan Areas				
$PM_{2.5}$	1.049^{***}	1.030^{***}	1.022^{**}	1.021^{**}
	[1.019, 1.080]	[1.026, 1.034]	[1.001, 1.043]	[1.004, 1.039]
Obs.	104	104	104	104
Panel C. Non-Metropolitan Areas				
$PM_{2.5}$	0.973	1.002	1.007	0.999
	[0.941, 1.007]	[0.984, 1.021]	[0.976, 1.040]	[0.967, 1.032]
Obs.	2,125	2,125	2,125	2,125
Common-Set of Controls		×	×	
Richer-Set of Controls				×
State Fixed Effects			×	×

Notes: This table shows regression estimates of COVID-19 mortality rate on annual $PM_{2.5}$ concentrations averaged from 2010 to 2018. Estimates as incidence rate ratios from Poisson regressions offsetting by population and clustering standard errors at the state level. Results in columns (3) and (4) of Panel I exclude Brasilia. Results in columns (3) and (4) of Panel III (B) include an Andean-fixed effect instead of state-fixed effects. Brackets show 95% confidence intervals. Significance levels: $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table B4: Long-Term Average $PM_{2.5}$ Exposure and COVID-19 Mortality Rate in Latin American Municipalities Above and Below the World Health Organization Annual Air Quality Guideline

	(1)	(2)	(3)
Panel A. All Municipalities			
$PM_{2.5}$ × Above Annual Guideline	1.017**	1.005	1.008
	[1.000, 1.035]	[0.994, 1.015]	[0.995, 1.022]
$PM_{2.5}$ × Below Annual Guideline	1.023	1.006	1.009
	[0.980, 1.068]	[0.980, 1.032]	[0.983, 1.036]
Obs.	9,235	9,235	9,235
Panel B. Metropolitan Areas			
$PM_{2.5}$ × Above Annual Guideline	1.016*	1.011*	1.024***
	[1.000, 1.032]	[0.999, 1.024]	[1.011, 1.037]
$PM_{2.5}$ × Below Annual Guideline	1.001	1.000	1.014
	[0.959, 1.046]	[0.968, 1.033]	[0.985, 1.044]
Obs.	1,587	1,587	1,587
Panel C. Non-Metropolitan Areas			
$PM_{2.5}$ × Above Annual Guideline	1.006	1.011**	1.006
	[0.9923, 1.021]	[1.002, 1.021]	[0.993, 1.019]
$PM_{2.5}$ × Below Annual Guideline	1.033*	1.028***	1.019
	[0.996, 1.071]	[1.008, 1.049]	[0.995, 1.043]
Obs.	7,648	7,648	7,648
Common-Set of Controls		×	×
Country Fixed Effects			×

Notes: This table shows regression estimates of COVID-19 mortality rate on annual $PM_{2.5}$ concentrations averaged from 2000 to 2018 by municipalities above and below the World Health Organization's Air Quality Guideline of 10 $\mu g/m^3$ of annual $PM_{2.5}$ concentrations. Estimates as incidence rate ratios from Poisson regressions offsetting by population and clustering standard errors at the state level. Observations are municipalities. Common-set includes explanatory variables as defined in Section 2. Brackets show 95% confidence intervals. Significance levels: $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.