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Review

COVID-19 and the Environment, Review and Analysis

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Abstract: We reviewed studies linking COVID-19 cases and deaths with the environment, focusing on relationships with air pollution. We found both short- and long-term observational relationships with a range of regulated pollutants, although only two studies considered both cases (i.e., infections) and deaths within a common analytical framework. Most of these studies were limited to a few months of the pandemic period. Statistically significant relationships were found more often for $PM_{2.5}$ and NO_2 than for other regulated pollutants, but no rationale was suggested for such short-term relationships; latency was seldom considered for long-term relationships. It was also unclear whether confounding had been adequately controlled in either type of study. Studies of air quality improvement following lockdowns found more robust relationships with local (CO, NO_2) rather than regional ($PM_{2.5}$, O_3) pollutants, but meteorological confounding was seldom considered. Only one of seven studies of airborne virus transmission reported actual measurements. Overall, we found the existing body of literature to be more suggestive than definitive. Due to these various deficiencies, we assembled a new state-level database of cumulative COVID-19 cases and deaths through March 2021 with a range of potential predictor variables and performed linear regression analyses on various combinations. As single predictors, we found significant ($p < 0.05$) relationships between cumulative cases and household crowding (+), education (−), face-mask usage (−), or voting Republican (+). For cumulative deaths, we found significant relationships with education (−), black race (+), or previous levels of $PM_{2.5}$ (+). NO_x (+), and elemental carbon (EC, +). We found no relationships between long-term air quality and cumulative COVID-19 cases. Our associations linking air pollution with COVID-19 mortality were not statistically different from those for all-cause mortality in previous studies. In multiple mortality regressions combining air pollution, race, and education, NO_x and EC remained significant but $PM_{2.5}$ did not. We concluded that the current worldwide emphasis on $PM_{2.5}$ is misplaced. We predicted air pollutant effects of a few percentage points, but individual differences between races, political identification, and post-graduate education were of the order of factors of 2 to 4. In general, the factors predicting infection were personal and related to COVID-19 exposure, while those predicting subsequent mortality tended to be more situational and related to geography. Overall, we concluded that how you live is more important than where you live.

Keywords: COVID-19; virus; air pollution; infections; mortality; lockdown; regression analysis

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1. Introduction

The medical literature now includes thousands of papers on COVID-19 and the coronavirus and includes environmental concerns, mainly with air pollution effects that cut both ways. Ambient air quality improves with reduced economic activity during lockdowns, i.e., virus effects on the ambient. There have been suspicions that susceptibility to the virus may have been enhanced by prior long-term exposures, i.e., ambient effects from the virus. Virus transmission by aerosol has also been hypothesized. While atmospheric changes can be readily monitored and modeled, human responses to the virus are not amenable to clinical study nor to cohort epidemiology. This leaves observational epidemiology as the only approach in understanding the substantial observed variations in COVID-19 related infections and deaths.

We reviewed this literature with regard to the following questions. How do lockdowns affect concentrations of specific pollutants and what are the implications for air pollution control strategies? Do studies of COVID-19 associations with ambient air quality comport with what has been learned from cohort and observational studies of other health endpoints? Is the virus transmission hypothesis consistent with existing knowledge of ambient particulate matter physics and chemistry? Although there may be additional issues with respect to solid and waste-water disposal, they are not considered here.

Our review of the extant COVID-19 air pollution epidemiology revealed some important shortcomings. There is little overlap between studies of rates of infections and of deaths. Pollutants have often been studied singly rather than in combination. Little attention has been given to the adequacy of confounder control. Associations with COVID-19 mortality have not been compared with those for other causes of death. To help fill these gaps, we present findings from a new study of air pollution of cases and deaths among US states.

2. Literature Review

The COVID-19 pandemic has spawned an enormous surfeit of new publications, over 120,000 at the time of writing, about 100,000 of which have open access. The earliest such paper [1] was published in January 2020 and warned of the dangers of "vaping and coronavirus". Note that this type of PubMed search picks up any mention of the search term, regardless of context. Requiring the search terms to include "air pollution" reduced the count to about 700, of which 90 were classified as review papers. Results of further successive search restrictions led to the following citation counts:

$PM_{2.5}$ or PM_{10}:	230
$PM_{2.5}$ or PM_{10} + NO_2:	137
$PM_{2.5}$ or PM_{10} + NO_2 + O_3	77
$PM_{2.5}$ or PM_{10} + NO_2 + traffic:	23
$PM_{2.5}$ + carbon (not CO)	5
traffic + carbon (not CO)	11
Indoor	81
time-series	20

Geographic distributions based on any mention were:

China:	213
Global:	160
Europe	110
India:	110
United States:	80
Canada:	35
California:	28
New York	25
Japan:	24
Africa:	19
South America:	14
Israel:	4

Air pollution has several contexts in this literature, the most common of which is concerned with air quality changes resulting from lockdowns or other travel restrictions. Next is associations with comorbidity that might affect vulnerability to the virus. The final category involves suspended particulates or aerosols as carriers for virus particles.

We selected 140 papers that seemed appropriate for detailed scrutiny. Of those, 5 were related to transmission, 30 to linkages with COVID-19 health effects, and 102 with the effect

of lockdowns on ambient air quality. Geographic diversity was most evident in the last category. A more extensive bibliography is presented as Appendix A.

2.1. Short-Term Associations between COVID-19 and Ambient Air Quality

Short-term analyses test the hypothesis that days with high rates of infection or mortality follow days with worse air quality [2]. Such analyses are based on daily rates of new cases or deaths and must allow for the COVID-19 incubation period, generally thought to be about 5 days. They must also consider other time-related factors including weather, holidays, and days of the week. All of the studies we considered met these requirements. Other factors that could introduce bias into such studies include delays in case reporting and differences between indoor and outdoor air quality.

These COVID-19 studies differ substantially from time-series studies of all-cause mortality that frequently require data over several years to achieve statistical significance, while these studies of COVID-19 comprised only a fraction of the total pandemic, typically a few months. All-cause mortality risks are generally only a few percentage points while the COVID-19 relative risk estimates may be around 1.5 or more.

Table 1 summarizes findings from the five short-term studies that we found and are quite similar despite their geographic diversity. Table 1 indicates whether the risk estimates were positive or negative and statistically significant; we could not compare their numerical risk estimates because of differences in the reporting metrics used. These are single-pollutant estimates that could have been influenced by inter-pollutant correlations and thus could be over-estimates.

Table 1. Summary of Short-Term Associations between COVID-19 Cases and Ambient Air Quality.

1st Author	Location	Time Period	Lag	$PM_{2.5}$	O_3	NO_2	SO_2	CO	PM_{10}
Adhikari [3]	Queens, NY	March, April 2020	21 d	−	**+**				
Hoang [4]	South Korea (1)	February, September 2020	7 d	+	−	**+**	**+**	+	+
	(2)			**+**	+	**+**	**+**	**+**	+
Jiang [5]	China (1)	February 2020	0	**+**	−	**+**	+	**+**	−
	(2)			**+**	−	**+**	**+**	**+**	−
	(3)			**+**	**+**	+	**+**	−	−
Li [6]	China (1)	February 2020	4 d	**+**		**+**		**+**	+
	(2)			**+**		**+**		−	**+**
Zhu [7]	120 Chinese cities	February 2020	21 d	**+**	**+**	**+**	−	**+**	**+**

+ = adverse, − = beneficial, **bold** = $p < -0.05$.

Short-term (daily) studies require precise timing of exposure and response that is limited by delays in case reporting and uncertainties in the virus incubation period. Most of the extant (non-COVID) studies of daily air pollution and mortality focused on the frail elderly, but this is not the case with COVID-19.

Table 1 comprises 45 risk estimates, of which only two would be statistically significant due to chance; here, we find 27 to be significant. $PM_{2.5}$ and NO_2 had the most consistently significant adverse short-term relationships.

There is substantial literature on the effects of daily perturbations in ambient air quality on daily mortality from all causes. For example, our analysis for Chicago [2] showed the importance of summing over the lag period and for adequate control of simultaneous temperature peaks. Effects of NO_2 in Table 1 ranged up to 6%; it thus remains to be seen whether any short-term COVID-related effects might be truly "excess". Our short-term studies of mortality and air pollution [2] also showed the importance of prior frailty and that only the frail elderly were at risk.

2.2. Long-Term Associations between COVID-19 and Ambient Air Quality

A long-term analysis, referred to as cross-sectional, tests the hypothesis that locations having high rates of infection are associated with places with worse long-term ambient air quality, typically based on cumulative cases or deaths. The underlying rationale is that such long-term exposures to polluted air would have resulted in co-morbidity that enhanced subsequent susceptibility to the virus. Such analyses must allow for comorbidity latency periods, often decades. In addition, they assume that the personal experiences of residents match the average properties of their residential locations, the so-called "ecological fallacy". This study design inherently compounds this issue of selectivity and representativeness; comorbidity studies typically find that air pollution affects only a small fraction of the population at risk, say 10% of those who contracted a disease, who comprise about 10% of those aged 20 or above based on heart disease, for example. The current cumulative rate of COVID-19 infection in the United States is about 9%; the odds of both pollution-related heart disease comorbidity and COVID-19 infection would thus be about 0.9%. About 1% of COVID-19 cases die from COVID-19, so the odds of both pollution-related heart disease comorbidity and COVID-19 mortality would be about 0.009%. The studies reviewed here (see below) may find that 25% of those were also associated with long-term air pollution, so that the combined cumulative air-pollution COVID-19 death rate could be about 22 per million population or about 1.3% of the total pandemic deaths in the US.

In addition, cross-sectional studies must account for personal characteristics of the participants (age, race, gender, smoking habit, income, body-mass index, stature) and community (population density, fraction of green space, traffic density, climate, socioeconomic status, elevation above sea level). In addition to meeting these design requirements, cross-sectional analysis requires accurate long-term exposure data for each of the air pollutants in the area under consideration, including indoor exposures.

Cross-sectional studies follow either of two modalities: studies of specific persons comprising a defined cohort, or studies of populations defined by residential location in which personal characteristics must be inferred from area-wide averages, often referred to as ecological. We found one COVID cohort study in our search but none of the seven studies met all of the requirements discussed above.

Table 2 summarizes the results of these studies in terms of air pollution associations, mostly with mortality as the endpoint. Particulate matter was studied most often, followed by NO_2 (or NO_x), and was positive and statistically significantly in 13 of the 18 estimates. There were no clear distinctions among endpoints or the nationalities studied. These studies covered a wide range of time periods up through September 2020 and were based on cumulative events.

Table 2. Summary of Long-Term Associations between COVID-19 and Ambient Air Quality.

1st Author	Location	Time Period	Outcome	$PM_{2.5}$	O_3	NO_2	SO_2	CO	PM_{10}
Bashir [8]	California	March, April 2020	cases	−		−		+	−
			deaths	−		−		+	−
De Angelis [9]	Italy	February–April 2020	cases	**+**		−			**+**
			death	**+**		−			+
Elliott [10]	UK	February, September 2020	death	**+**		+			**+**
Liang [11]	US countries	February–July 2020	death	**+**	−	**+**			
			case-fat rate	+	−	**+**			
Magazzino [12]	NY state	March–June 2020	death	**+**		**+**			
Magazzino [13]	France (1)	March–April 2020	death	**+**					**+**
	(2)		death	**+**					**+**
	(3)		death	**+**					**+**
Mendy [14]	Cincinnati, OH	March–July 2020	hospitalization	**+** (only with prior asthma or COPD)					
Neelon [15]	US counties	March–August 2020	death	**+**					
Wu [16]	US counties	February–April 2020	death	**+**					

+ = adverse, − = beneficial, **bold** = $p < -0.05$.

It is important to realize that none of these air pollution studies involved personal exposures and that studies of the entire US or UK involved modelled rather than measured concentrations. None of those studies considered latency periods and only Elliott et al. [10] considered truly long-term (10 y) exposure. The correct interpretation of these associations is thus that COVID-19 may be more severe in locations with higher particulate concentrations but it cannot be assumed that outdoor air quality was responsible for these outcomes.

3. Air Quality Considerations

3.1. Effects of Pandemic Restrictions

To limit virus transmission, most political jurisdictions restricted business and personal activities during the pandemic, often approaching lockdowns and characterized by deserted freeways and public spaces. The resulting reductions in emissions improved air quality and provided unparalleled opportunities to evaluate potential air pollution control strategies. The literature includes numerous examples of major cities around the world, especially in Asia, and often emphasizing fine particles ($PM_{2.5}$). Here, we review papers that appear to be of general applicability. Most of them compared ambient concentrations before and during lockdown, several compared values before, during, and after lockdown, and Bekbulat et al. [17] also considered seasonal corrections. Most studies were based on routine monitoring data from regulatory networks. Chauhan and Singh [18] focused on $PM_{2.5}$ and reported reductions ranging from 4% to 32% worldwide, corresponding to a median reduction of about 11%.

Hudda et al. [19] deployed research-grade instruments in a mixed residential–commercial neighborhood near Boston, MA, measuring black carbon (BC) mass concentrations and ultrafine particle (PNC) number concentrations. Truck and car traffic dropped by 46% and 71%, respectively and BC and PNC concentrations decreased by 34% and 64%, for an essentially linear response. BC concentrations were 50% lower and NO_2 concentrations were about 40% lower at nearby routine air quality monitoring sites. However, changes in $PM_{2.5}$ levels were inconsistent, −9% near the freeway and −52% at an urban background site.

Bekbulat et al. [17] used routine air quality monitoring data for the entire US for $PM_{2.5}$, PM_{10}, O_3, NO_2, and CO. They used models to estimate "expected" ambient concentrations during lockdown periods, thus adjusting for seasonal trends. They concluded that $PM_{2.5}$ concentrations were not reduced below their normal range of variability and that PM_{10}, O_3, NO_2, and CO level reductions were "modest and transient".

Chen et al. [20] compared routine monitoring data for 28 metropolitan areas in terms of percent changes rather than actual concentrations. We took their analysis a step further and used linear regressions to compare the lockdown changes by pollutant. The empirical equation for the reduction in $PM_{2.5}$ by city shown in Figure 1 is

$$\Delta PM_{2.5} = 26 + 1.22\ (0.61 - 1.82)\Delta NO_2 \quad (R = 0.63) \tag{1}$$

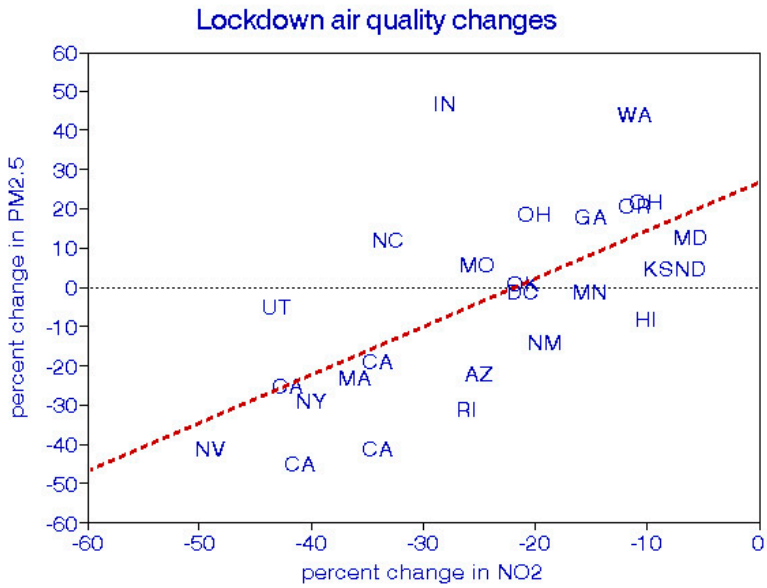

Figure 1. Change in ambient $PM_{2.5}$ by change in NO_2 during lockdown in 28 US cities based on data from Chen et al. (2020). Plotting symbols represent state abbreviations.

Note that the regression coefficient is not significantly different from unity, suggesting that lockdowns had equivalent effects on both pollutants that may be interpreted as the traffic-related contributions to $PM_{2.5}$, but that the intercept (26 $\mu g/m^3$) indicates the importance of non-traffic sources. In the absence of traffic, the lockdowns have apparently increased $PM_{2.5}$ (the data points for IN (Indianapolis) and WA (Seattle) are both statistically significant). This suggests that sources of non-traffic $PM_{2.5}$ were not affected by the lockdown and has implications with respect to air pollution control strategies.

We also developed regression equations for CO and O_3:

$$\Delta CO = -2.6 + 0.48\ (0.09 - 0.90)\Delta NO_2 \quad (R = 0.49) \tag{2}$$

$$\Delta O_3 = -6.4 - 0.20\ (-0.55 - 0.15)\Delta NO_2 \quad (R = -0.22) \tag{3}$$

Equation (2) shows that percentage reductions in CO are significantly associated with those for NO_2 at about half of the value, and that there are no other sources (intercept = ~0). Equation (3) confirms that the lockdown had no discernable effect on O_3.

Jephcote et al. [21] analyzed air quality data for the entire UK during lockdown periods and concluded that traffic was reduced by 69% overall, NO_2 by 38%, and $PM_{2.5}$ by 16%. Reductions were greatest at urban traffic sites and less at more residential locations. Xiang et al. [22] presented a more detailed analysis of a lockdown in Seattle and reported that adjusting for changes in meteorology can be important.

3.2. Indoor Air Quality

Coping with the pandemic raises various air quality issues [23]. People spend essentially all of their time indoors during lockdown, thus reducing effects of outdoor emissions and potentially improving ambient air quality. Effects on indoor air quality depend on infiltration from the outdoors, use of air conditioning or ventilation systems, use of sanitation solvents, increased physical activity and cooking, and use of fireplaces. Many of these factors are climate dependent. Long-term indoor air quality during the pandemic is likely to differ substantially from pre-pandemic levels. In any event, outdoor air quality during the pandemic has been an inadequate measure of actual exposures. Recent guidance from the Centers for Disease Control calls for substantially increased outdoor ventilation that would also complicate air pollution epidemiology in terms of increasing the diversity of personal exposures. Unfortunately, the literature on this topic is quite sparse.

The situation with short-term exposures as used in time-series analysis is quite different [2]. About 50% of outdoor air pollution penetrates indoors with essentially the same frequency distribution, while the contributions of indoor sources remain constant. Thus, any time-dependent associations with daily outdoor air quality will also relate to indoor environments. As a result, short-term air pollution associations are inherently more credible than long-term.

Dominguez et al. [24] reported that outdoor $PM_{2.5}$ declined from 11 to 7 $\mu g/m^3$ during lockdown in Madrid while indoor levels rose by 12%, presumably as a result of increased indoor activities. Much larger indoor increases were reported for volatile organic compounds (VOCs).

3.3. Air Pollution and Virus Transmission

In this section, we review what has been published on airborne particulate matter as a virus carrier thereby exerting direct effects on COVID-19 infections. Most of these papers discussed the "possibilities" of the hypothesis, based on biology and factors controlling lung penetration and deposition, which are highly dependent on particle size and composition. However, data on ultrafine particles that might be the most logical carriers are extremely sparse [21]. The paper by Chirizzi et al. [25] is a notable exception, based on actual PM_{10} measurements in Italy and determination of accompanying genetic material. They used a cascade impactor to separate the collected material into 12 size ranges and concluded that "Outdoor air in residential and urban areas was generally not infectious and safe for the general public in both northern and southern Italy, with the possible exclusion of very crowded sites". Faridi et al. [26] collected particles sized from 0.25–32 μm near hospitalized COVID patients; they tested negative based on the Reverse Transcription PCR test.

4. Cross-Sectional Analysis of Air Quality and Cumulative COVID-19 Cases and Deaths by State

The preceding review of long-term COVID-19 relationships with ambient air quality, focused on mortality covered modest periods of the pandemic, used single-pollutant analyses without considering interactions with non-pollutant factors, and showed heterogeneous results. Here, we use state-level data [https://www.nytimes.com/interactive/2020/us/coronavirus-us-cases.html] through 20 March 2021, in conjunction with census data to estimate relationships with previous average levels of $PM_{2.5}$, NO_x, and elemental carbon

(EC) [27,28]. The variables used are state-wide averages (Table 3). Cumulative COVID-19 cases and deaths are expressed in terms of one million persons and the analysis is limited to the contiguous United States and the District of Columbia.

Table 3. Variables Used in Cross-Sectional Analysis and Univariate Correlations by State.

	Mean (Median)	Case Corr	Death Corr	Case Δ%/Unit	Death Δ%/Per Unit
Cases per million	(87,601)				
Deaths per million	(1458)				
Case-fatality rate	0.0173				
Population density (sq mi) *	(524)	−0.08	0.22		
Persons per household *	2.58	**0.51**	0.08	**16**	
% Black residents *	11.5	0.05	0.35		**1.4**
% Hispanic residents *	11.2	0.13	0.19		
Household income *	$52,400	−0.20	−0.05		
Education level index *	51	**−0.38**	−0.33	**−4.9**	**−5.1**
% Republican voters **	50	**0.51**	0.12	**1.4**	
Face mask usage score ***	298	**−0.30**	0.12	**−4.9**	
Distance from NYC ****	688	0.14	−0.26		
$PM_{2.5}$ (2003) $\mu g/m^3$ *****	11.8	0.07	**0.34**		**5.2**
$PM_{2.5}$ (2016) $\mu g/m^3$ *****	8.2	0.14	0.26		
NOx (2002), ppb [27]	7.1	−0.08	**0.32**		**2.1**
EC (2002) $\mu g/m^3$ [27]	0.29	0.11	**0.30**		**4.5**

(median), **bold** = $p < 0.05$ * U.S. Census data ** election results *** NY Times, 7/17/2020 **** road atlas ***** US EPA Air Data.

4.1. Data and Methods

We present median values for variables having substantially skewed distributions. Note that the total US case and death counts would be 29 million and 480 thousand when based on the US population of 330 million, consistent with press reports at that time. Our analysis is not population-weighted; we consider each state to be an independent sample of the nation for statistical purposes. For example, Vermont and California data carry the same weight.

4.2. Results

We made 26 univariate significance tests in Table 3 of which we would expect one to be significant at the 95% confidence due to chance. However, we obtained nine, all of which had the expected signs, negative for education and mask use and positive for household crowding and air pollution. We expected many of these variables to be intercorrelated; multivariate regressions would thus be required to test for independence. As we are primarily interested in air pollution, we confined this part of the analysis to relationships with deaths and added the variables for Black residents and education level to the regressions for $PM_{2.5}$, NO_x, and EC Equations (4)–(7).

$$\ln(\text{deaths/million}) = 7.22 + 0.0304\ (0.024)\ PM_{2.5} - 0.0074\ (0.0042)\ \text{education} - 0.0066\ (0.0062)\%\ \text{Black} \quad (4)$$

$$\ln(\text{deaths/million}) = 7.78 + 0.0282\ (0.0106)\ NO_x - 0.0138\ (0.0046)\ \text{education} + 0.00002\ (0.0006)\%\ \text{Black} \quad (5)$$

$$\ln(\text{deaths/million}) = 7.72 + 0.652\ (0.255)\ \text{EC} - 0.0142\ (0.0048)\ \text{education} - 0.00002\ (0.0007)\%\ \text{Black} \quad (6)$$

$$\ln(\text{deaths/million}) = 7.56 + 0.0252\ (0.0095)\ NO_x + 0.0163\ (0.022)\ PM_{2.5} - 0.0127\ (0.0042)\ \text{education} \quad (7)$$

These relationships indicate that NO_x and EC (both of which relate to vehicular traffic) remain significant in multi-variable regressions by contrast with that for $PM_{2.5}$, but NO_x prevails when regressed jointly with $PM_{2.5}$ Equation (7) and education prevails over skin color, as expected.

Figures 2–4 display linear relationships with COVID-19 and personal characteristics. The patterns for cases and deaths are similar, indicating systematic effects. These graphs indicate that some low-COVID states (WA, OR, ME, VT) have low crowding, more education, and fewer Republicans, perhaps suggesting synergism. These low-COVID states would appear to be relatively more important if a linear y-axis had been used. Figures 5 and 6 also show that these low-risk states also have better air quality.

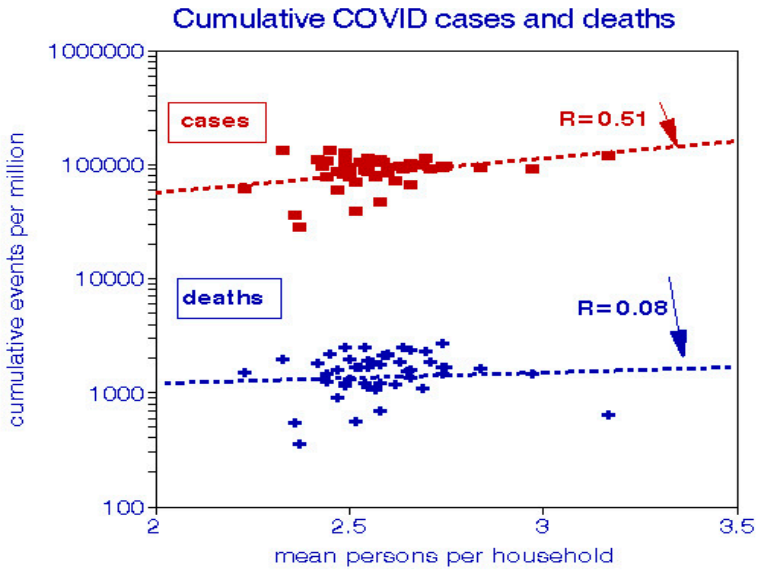

Figure 2. Relationships with household crowding.

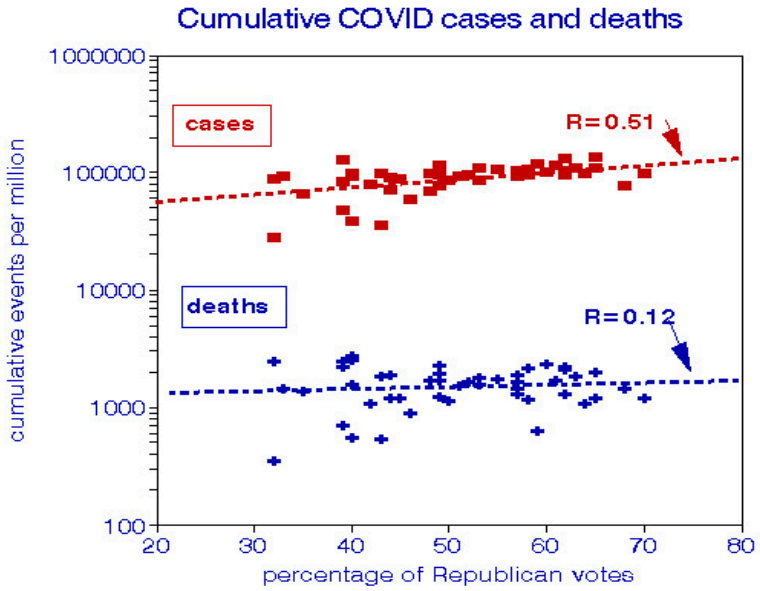

Figure 3. Relationships with Republican voters in the national election.

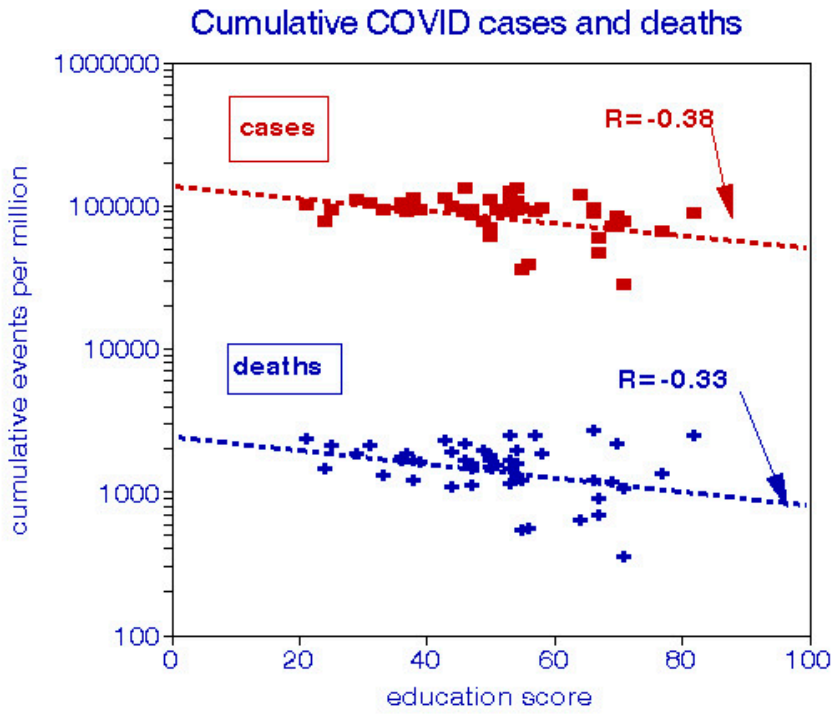

Figure 4. Relationships with education score.

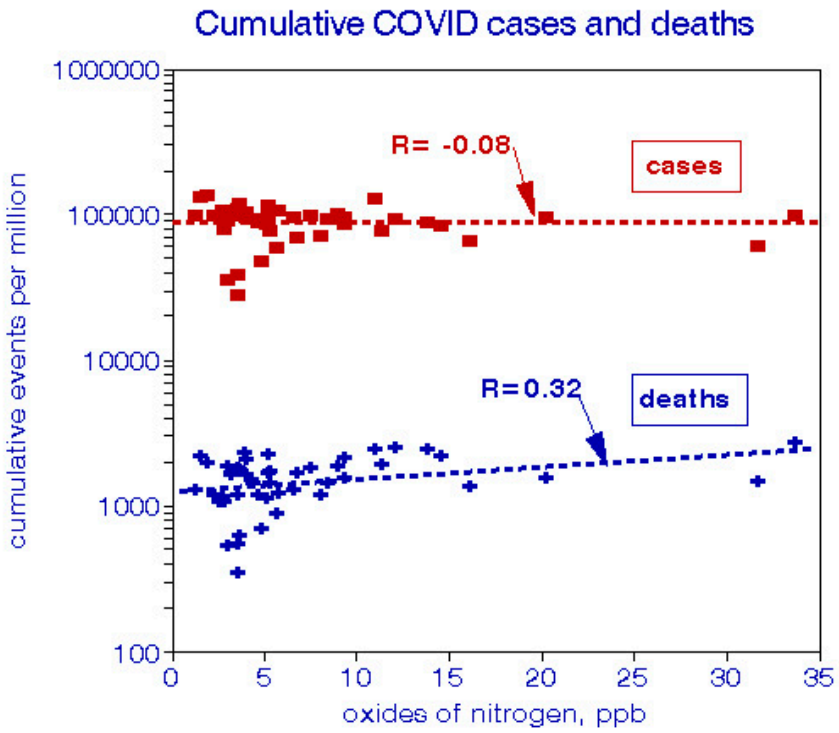

Figure 5. Relationships with NO_x.

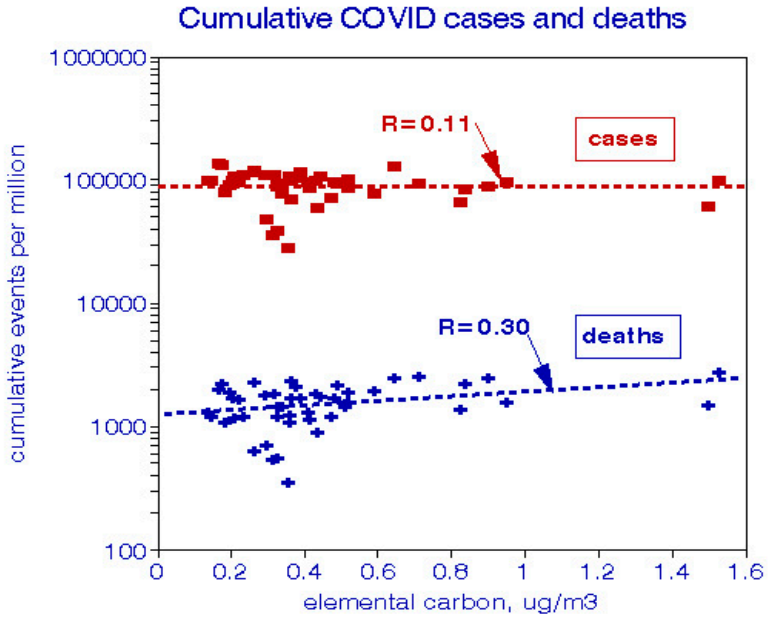

Figure 6. Relationships with EC.

4.3. Regression Analysis Discussion

The independent variables in Table 3 comprise two categories: personal (education, face mask use, political affiliation, income, education, persons per household) for which the individual has some control, and situational (population density, race, distance from New York City, air quality), for which the individual has little or no control. Our results indicate that COVID-19 cases tend to be associated with personal factors and deaths associated with situations.

We also note that the relative magnitudes of change are small and trivial with respect to the range of variations among states as seen in Figures 2–6. Cases vary by about a factor of 5 among the states and deaths vary by about a factor of 8; Table 3 thus indicates that only small portion of the variance among states (maximum of 26% of the variance) can be explained by reasonable increments in these variables, statistical significance notwithstanding. However, classification variables like percentages of Black residents or Republican voters can also be compared on the basis of yes (100%) or no (zero), which yields factors of 2–4 for deaths or CFRs for Blacks and factors of 3–4 for Republicans. The range for mask usage is about a factor of 2 as is the maximum education effect. The latter is consistent with published data comparing high school with postgraduate education. Longitudinal studies show that the national COVID-19 case "waves" range over about a factor of 10, while a Black, poorly educated, Republican without a mask could experience a mortality risk level of about $3 \times 3.5 \times 2 \times 2 = 40$, assuming that all factors were independent, (however unlikely).

Most of our predictor variables serve as indicators and should not be taken literally. Voting Republican is not lethal and receiving a university diploma is not in itself life-saving. Rather, these parameters serve to indicate compliance with COVID-19 exposure guidelines or following healthy lifestyles. Higher education is associated with lower risks of both infection (less exposure) and subsequent mortality (less smoking, lower body-mass index, less comorbidity). Our significant air pollutants (EC, NO_x) relate to vehicular traffic density as in city centers and encapsulate effects of noise, dust from tires and brake pads and lubrication oil combustion products. We interpret these relationships as pertaining to the locations and land-use patterns that have been stable over time, rather than to personal exposures that may have varied.

It is also pertinent to compare COVID-19 with all-cause mortality risks associated with air pollution, shown in Table 4 on the basis of mean concentrations. There are no significant differences, indicating that the air pollution effects shown in Table 3 may have occurred

with or without the pandemic. Note that the pandemic risk estimates are controlled for Black race, while these all-cause cohort estimates were controlled for a number of personal and location-specific characteristics [27,28]. As cases and deaths share common temporal and spatial relationships, the case-fatality ratio (CFR) is somewhat less variable. We found that NO_x and EC were significant predictors of CFRs but with smaller incremental effects.

Table 4. Relative mortality risks of air pollution by cause of death.

Pollutant	COVID-19 Mortality *	All-Cause Mortality #
EC	1.07 (0.94–1.23)	1.07 (1.05–1.10)
NO_x	1.10 (0.95–1.26)	1.08 (1.06–1.09)
$PM_{2.5}$	1.48 (0.84–2.62)	1.09 (0.90–1.33)

* controlled for race. # from previous studies.

4.4. Summary of the New Analysis

This analysis is based on state-to-state differences in COVID-19 cases and deaths accumulated over the entire pandemic through mid-March 2021. The predictor variables we used are assumed to have remained fixed during the pandemic, which is clearly not the case with face mask usage, for example. The predictor variables for cases relate to exposures, including crowding and face-mask usage, and they relate to susceptibility such as race or previous exposure to air pollution with respect to deaths. Above, we combined the probability of enhanced susceptibility from prior air pollution with the probability of a COVID-related death and estimated the combined air pollution risk of COVID death as a few percentage points, at most. This cross-sectional analysis (Table 3) is consistent with this estimate and shows that traffic-related pollutants are more likely to be involved than $PM_{2.5}$. Our most important findings are those relating to preventing infection (cases). Those factors are individually actionable and supported by previous (non-COVID-19) estimates. By contrast, our estimates of air pollution—COVID mortality risks provide no evidence that they might exceed those associated with all-cause mortality during this period.

5. Overall Conclusions

Although a large body of literature exists on air pollution and COVID-19, much of it shares common shortcomings: limited coverage of the pandemic period, considering only one pollutant at a time, and inadequate consideration of confounding. We found no physiological rationale for the hypothesis that air pollution might increase daily rates of infection (cases). The extant COVID-19 epidemiology tests the hypothesis that a given pollutant, often $PM_{2.5}$, is statistically significantly associated with either cases or deaths having "controlled" for selected confounders. No assurance is given that such controls were adequate or that other pollutants might be important or that the presumed exposures were appropriate. More research is needed on the viral content of airborne particles as a function of size and chemistry.

An important lesson from the air quality changes during lockdowns is the insensitivity of $PM_{2.5}$ and O_3 to drastic reductions in central city emissions in contrast with traffic-related pollutants, in this case NO_x and EC. Possible explanations include dominance of other than combustion-related species, contributions from distal sources with elevated releases such as power plants, or changes in atmospheric chemistry. These unplanned intervention experiments should be analyzed in detail.

Our regression analysis of current cumulative COVID-19 cases and deaths fills some of these gaps, especially temporal. We show that air pollution relationships pertain to deaths and not cases and that their contributions are much smaller than those of personal factors like race and education. We show that each of the three pollutants we considered were significantly associated with cumulative COVID-19 deaths as a single predictor, but that only NO_x and EC remained significant in multi-variate regressions. Since only prior exposures are relevant to COVID-19 mortality, the diminution of those pollutants during

lockdowns are of no consequence (but might have conferred subsequent benefits). Our analysis also showed that adverse health effects may be associated with un-regulated pollutants such as EC.

All of the long-term COVID-19 air pollution epidemiology studies, including ours, share problems of exposure misclassification with regard to time and place. If the operational hypothesis is the importance of prior exposures, a cohort analysis must consider the total accumulated respiratory burden, similar to pack-years in smoking studies, that is given by all of the exposures of each individual, indoors and out. By contrast, a time-series analysis must consider all individuals at risk to exposures that occurred within a reasonable lag period. A long-term study must sum the exposures of each individual; a short-term study must sum responses of all individuals to a given day's exposure. Unfortunately, few studies have respected these precepts.

We found no support for the hypothesis that $PM_{2.5}$ might be an important factor in the COVID-19 pandemic. Further, we showed that the relationships between air pollution COVID-19 deaths are no different from those reported for deaths from all causes and that the COVID-19 deaths are thus not "excess". Context is important in epidemiology.

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Appendix A

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