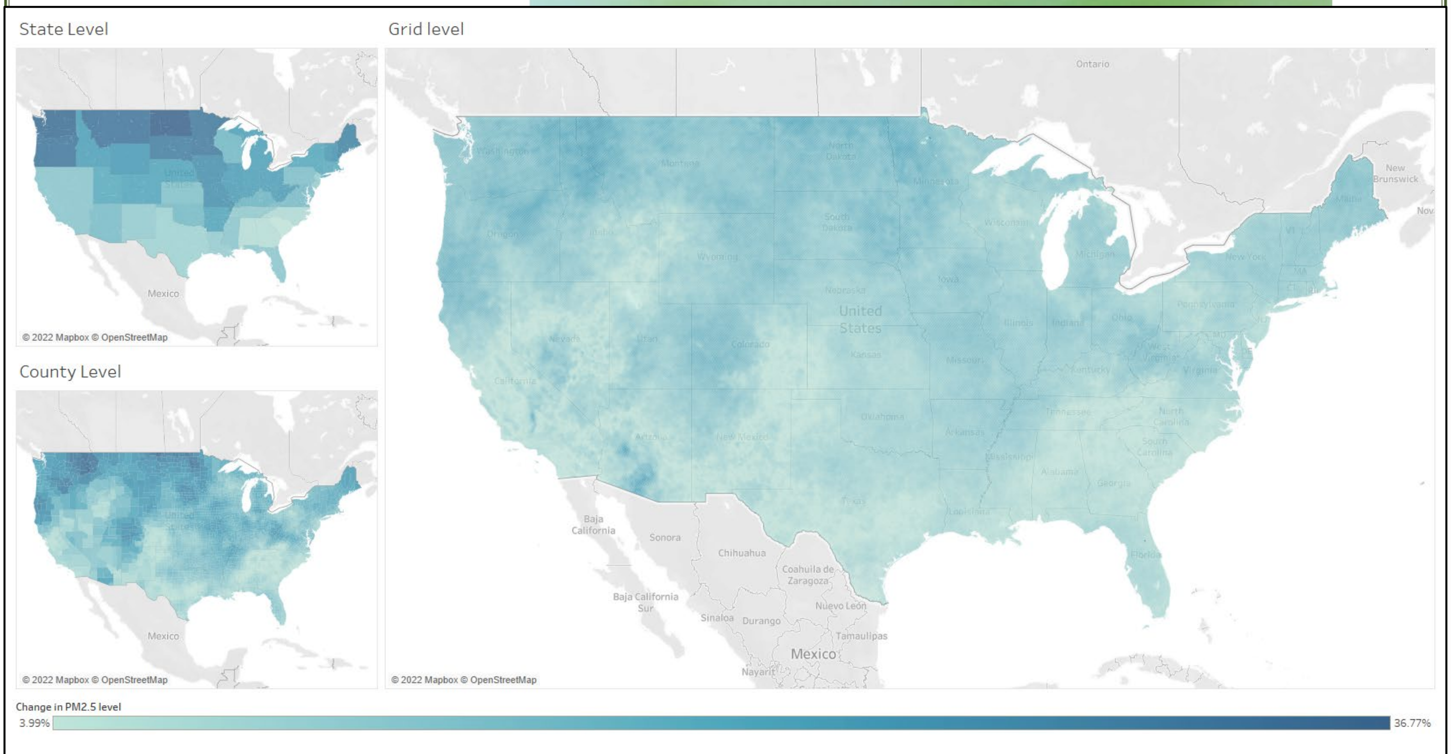
EFFECTS OF COVID-19 LOCKDOWN ON AIR QUALITY AND MORTALITY ACROSS CONTIGUOUS UNITED STATES—A DATA-DRIVEN APPROACH



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16. Abstract

Premature death from cardiovascular and respiratory disorders can be attributed to poor air quality. Lockdowns enacted by numerous countries during the continuing COVID-19 outbreak resulted in a significant improvement in air quality throughout the world. Different lockdown measures in the contiguous United States were analyzed to see how they affected air pollution and the health of people in the short and long term. Using data from more than 500 monitoring sites across the contiguous United States, as well as satellite data, researchers created a high-resolution map of concentrations of particulate matter 2.5 microns or less in width ($PM_{2.5}$). Health benefits, reported in terms of short-term and long-term averted mortality from $PM_{2.5}$ exposure, were assessed using the most recent epidemiological data on COVID-19 pandemic treatments. Different economic recovery scenarios (immediate or gradual resumption of activities, a second outbreak in winter, and permanent lockdown for the whole of 2021) were used to examine the long-term variability in air quality and the accompanying premature mortality. According to these findings, lockdown actions in the contiguous United States significantly reduced $PM_{2.5}$ concentrations. However, researchers found considerable variations between different states in the number of premature deaths that may be attributed to air pollution. It is possible to significantly improve air quality if strict emission control regulations are put into place.

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Executive Summary

Premature death from cardiovascular and respiratory disorders can be attributed to poor air quality. Lockdowns enacted by numerous countries during the continuing COVID-19 outbreak resulted in a significant improvement in air quality throughout the world. Different lockdown measures in the contiguous United States were analyzed to see how they affected air pollution and the health of people in the short and long term.

Using data from more than 500 monitoring sites across the contiguous United States, as well as satellite data, researchers created a high-resolution map of concentrations of particulate matter 2.5 microns or less in width ($PM_{2.5}$). Health benefits, reported in terms of short-term and long-term averted mortality from $PM_{2.5}$ exposure, were assessed using the most recent epidemiological data on COVID-19 pandemic treatments. Different economic recovery scenarios (immediate or gradual resumption of activities, a second outbreak in winter, and permanent lockdown for the whole of 2021) were used to examine the long-term variability in air quality and the accompanying premature mortality.

$PM_{2.5}$ levels have decreased by up to 100 percent in most states. Nitrogen dioxide also showed a similar pattern of reduction during the COVID-19 period. It was anticipated that the enhanced air quality during the lockdown period would reduce short-term premature mortality related to $PM_{2.5}$ concentrations, particularly in the weeks after the implementation of stringent control measures. During the lockdown period in the United States, an estimated maximum of 6489 premature deaths were saved (95 percent confidence interval: 4960–6440) compared to the averages for 2016–2019.

Based on the findings of this study, it was observed that lockdown measures in the contiguous United States significantly reduced PM2.5 concentrations. However, considerable variations were found between different states in the number of premature deaths that could be attributed to air pollution. The study suggests that it is possible to significantly improve air quality if strict emission control regulations are implemented.

Table of Contents

List of Figures

List of Tables

Background and Introduction

The COVID-19 pandemic, which originated in Wuhan, China, in December 2019 (Zhou et al., 2020), has become the most disruptive health hazard since the Spanish flu pandemic of 1918–1919 (Taubenberger, 2006). The social impacts of COVID-19 are even more pronounced as travel restrictions, quarantine, and social distancing have now become the new normal to slow down the spread of SARS-CoV-2 (Anderson et al., 2020). Face masks for the limited time spent outside or in public spaces have been mandatory in the most affected countries (Bedford et al., 2020).

CARTEEH QUICK FACTS

CARTEEH is a Tier 1 University Transportation Center, funded by the U.S. Department of Transportation's Office of the Secretary for Research and Technology.

Although the consequences of COVID-19 are indiscriminately catastrophic for society and the U.S. economy, extreme lockdown measures in the United States led to an abrupt decline in anthropogenic air pollution in the United States. The decline of anthropogenic air pollution in the countries that have responded to COVID-19 was observed in preliminary assessments. According to the National Aeronautics and Space Administration (NASA) Earth Observatory, satellite-derived concentrations of particulate matter 2.5 microns or less in width ($PM_{2.5}$) in China's eastern and central regions were 10–30 percent lower than those for the same dates in 2019 (Patel, 2020). According to the European Environment Agency, air pollution in European cities decreased significantly (European Environmental Agency, 2020). When compared to the same dates in 2019, Bergamo, Italy (47 percent), and Barcelona, Spain (55 percent), demonstrated significant decreases in $PM_{2.5}$ concentrations. While satellite data of air quality provide a useful estimate of large exposures, a correlating value of pollution trends by using in-situ measurements is necessary to accurately evaluate the impact (Bechle et al., 2013).

In terms of pollutant concentrations, ground-based measurements are the gold standard and the go-to technique for ensuring compliance with regulations. In areas with extensive monitoring networks, measured air pollution concentrations can be used to examine changes in pollution levels. The influence of COVID-19 on air quality in the United States has been the subject of several investigations. Most research has compared ground-based observation data between pandemic and non-pandemic eras using 5-year (or 3-year) average air quality from 2015 (or 2017) to 2019 as the baseline non-pandemic conditions. The fast changes in human activity in urban areas have resulted in more severe air quality changes than in rural regions. Nitrogen oxide reductions in the United States are typically steady although $PM_{2.5}$ and PM_{10} concentrations show a wide range of changes throughout areas of the country and the globe.

One recent study used the county-level pollution concentration data from the AirNow database between historical and COVID-19 periods (Berman et al., 2020). The counties were disaggregated by the institution of early or late non-essential business closures. Statistically significant $PM_{2.5}$ declines, particularly in urban counties, were observed during the current COVID-19 period compared to historical data: a 25.5 percent reduction with an absolute decrease of 4.8 ppb (Berman et al., 2020). This study's use of AirNow data poses a potential limitation because recent measurements are not yet verified for quality assurance. In the case of $PM_{2.5}$, only 18 percent of available observation sites in the United States showed a decrease in concentrations during April 2020. The comparisons of monthly averaged $PM_{2.5}$ concentrations between five previous Aprils from 2015 to 2019, and April 2020, were reported by Archer et al. (2020). Air Quality System (AQS) sites in California and several AQS sites in the eastern United States reduced $PM_{2.5}$ levels by 1–7 ug/m^3.

However, $PM_{2.5}$ concentrations rose in most parts of the United States, reaching up to 34.1 percent in Florida. On average, there was an estimated 0.05 ug/m^3 increase in $PM_{2.5}$ during April 2020 compared to the previous 5 years. The impact of the shelter-in-place order varied between rural and urban areas. Reduced vehicle travel and thus vehicle emissions due to the shelter-in-place order mainly occurred in urban areas.

However, in addition to vehicle emissions, power plants, residential wood burning, forest fires, and agricultural burnings are significant sources of $PM_{2.5}$, and the lockdown had little effect on these emissions. Reducing nitrogen oxide emissions could also make the atmosphere more reactive, which could lead to more nitrate, sulfate, and secondary organic aerosols in $PM_{2.5}$.

Problem

The literature review found that the lockdown policy and stay-at-home order led to the reduction of transportation activity across the United States, which led to the decrease of gas-phase atmospheric pollutants. However, in the case of particulate matter, the distribution was nonuniform. Also, no studies have combined the satellite data with ground measurement station data to evaluate the air quality impact of COVID-19 in the contiguous United States.

This study aimed to investigate the effectiveness of control measures, such as those implemented during the COVID-19 pandemic, in reducing the mortality burden due to air pollution, which remains the leading environmental cause of death to date. Specifically, this investigation focused on fine particulate matter ($PM_{2.5}$), which is both directly emitted by human activities and formed through chemical reactions in the atmosphere.

Approach

This study aimed to integrate observational air quality data from the U.S. Environmental Protection Agency (EPA) and other state agencies' monitoring networks with satellite data and epidemiological studies to quantify, on short-term and long-term scales, the health benefits of the lockdown measures imposed in response to the COVID-19 pandemic. The research team analyzed the role of different emission sectors and systems as well as the role of meteorology in contributing to the observed decrease in $PM_{2.5}$ concentrations.

The research team compared the mortality burden from COVID-19 to the avoided deaths resulting from improved air quality. In addition, the team explored the human, social, and political dynamics leading to different risk perceptions associated with the COVID-19 pandemic versus a global environmental crisis, and the implications of these differences for policy making.

Methodology

The research plan was divided into five tasks.

Task 1: Project Management

The aim of this task was to complete the required contractual processes and kick off the project and to maintain ongoing compliance with CARTEEH project and grant requirements.

Task 2: Data Extraction and Processing

Researchers extracted remote sensing aerosol optical diameter (AOD) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) Terra satellite using the MAIAC retrieval algorithm. The algorithm was calibrated by Aerosol Robotic Network (AERONET) surface data at 1-km-resolution grid cells across the United States from January 1, 2016, to December 31, 2020. Also, ground-based observations of $PM_{2.5}$ concentrations from more than 1250 active $PM_{2.5}$ measurement sites across the contiguous United States were retrieved for the same data period. The baseline satellite data $PM_{2.5}$ concentrations, which represent an underlying spatial field for each point in the specified domain, were integrated with observed in-situ data, which provided up-to-date and direct information on $PM_{2.5}$ concentrations. This approach helped to overcome issues related to spatial availability and accuracy of the data. $PM_{2.5}$ daily means were computed at each site after preprocessing steps to ensure data quality.

Task 3: Estimation of $PM_{2.5}$ Mortality

Using an exposure response function based on 110 peer-reviewed epidemiological short-term time-series studies of daily death and hospital admissions, the short-term mortality burden saved during the lockdown period was calculated on each day (Atkinson et al., 2014). The total mortality burden (M) in each grid cell and day was computed as follows (Apte et al., 2015):

$$M = B_d \times P \times \frac{RR - 1}{RR}$$

where B_d is the daily, country-specific baseline risk of deaths from non-communicable diseases, obtained from the Global Burden of Diseases, Injuries, and Risk Factors Study 2017 (Dicker et al., 2017); P is the total population in each grid cell from census population data; and RR is the relative risk, defined as:

$$RR = \exp\left(\gamma \times \left(PM_{covid} - PM_{preCOVID}\right)\right)$$

where PM_{COVID} is the daily mean $PM_{2.5}$ concentration (in µg m^{-3}) for 2020, $PM_{preCOVID}$ is the average for 2016–2019, and γ is the excess mortality per unit increase in $PM_{2.5}$ (Atkinson et al., 2014).

Task 4: Scenario Evaluation for Economic Restoration

The four pathways of economic recovery envisioned in this work are:

- Immediate restart.
- Gradual restart.
- Fall/winter outbreak.
- Permanent lockdown.

Figure 1 depicts the methodology's general technique.

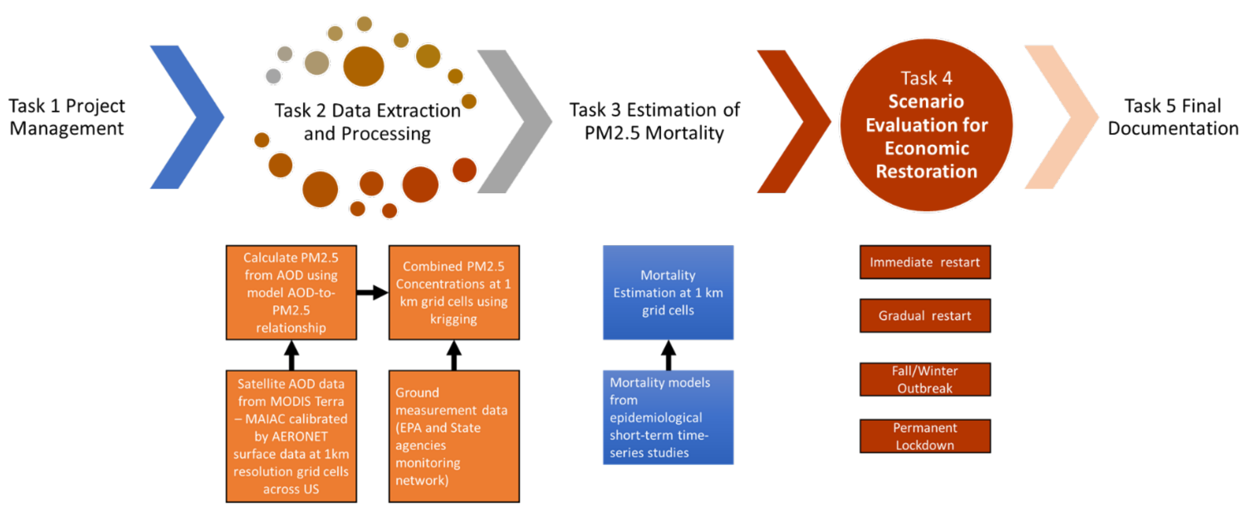

Figure 1. Overall methodology.

Task 5: Final Documentation

At the conclusion of the data analysis activities, a final report documenting the work performed, methodologies, outcomes, and next steps was developed. The deliverables included a final project report, visualization dashboard, and briefing material (in the form of a PowerPoint presentation).

Results

Ground Monitoring Station Results

As the first step in data retrieval, daily average values of all the monitors managed by EPA were downloaded for the two data periods: the pre-COVID-19 period (2015–2019) and the COVID-19 period (2020). EPA releases preprocessed daily data for different pollutants on the Airnow website.[1] Located around the contiguous United States, 513 monitoring stations measure $PM_{2.5}$. The data were quality checked and contained the daily mean, maximum, minimum, and other statistics for different pollutants. Two pollutants were considered: $PM_{2.5}$ and nitrogen dioxide (NO_2). NO_2 was chosen in addition to $PM_{2.5}$ because it is a better indicator of traffic-induced air pollution. The change in daily average levels were visualized by computing the percentage change during the COVID-19 period compared to the pre-COVID-19 period. The results were aggregated to the state level for visualization purposes. As Figure 2 shows, the $PM_{2.5}$ levels have decreased up to 100 percent in most of states. NO_2 also showed a similar pattern of reduction during the COVID-19 period. The visualization was uploaded to the CARTEEH data hub and is available at https://carteehdata.org/library/webapp/effects-of-covid-19-lockd-ab39.

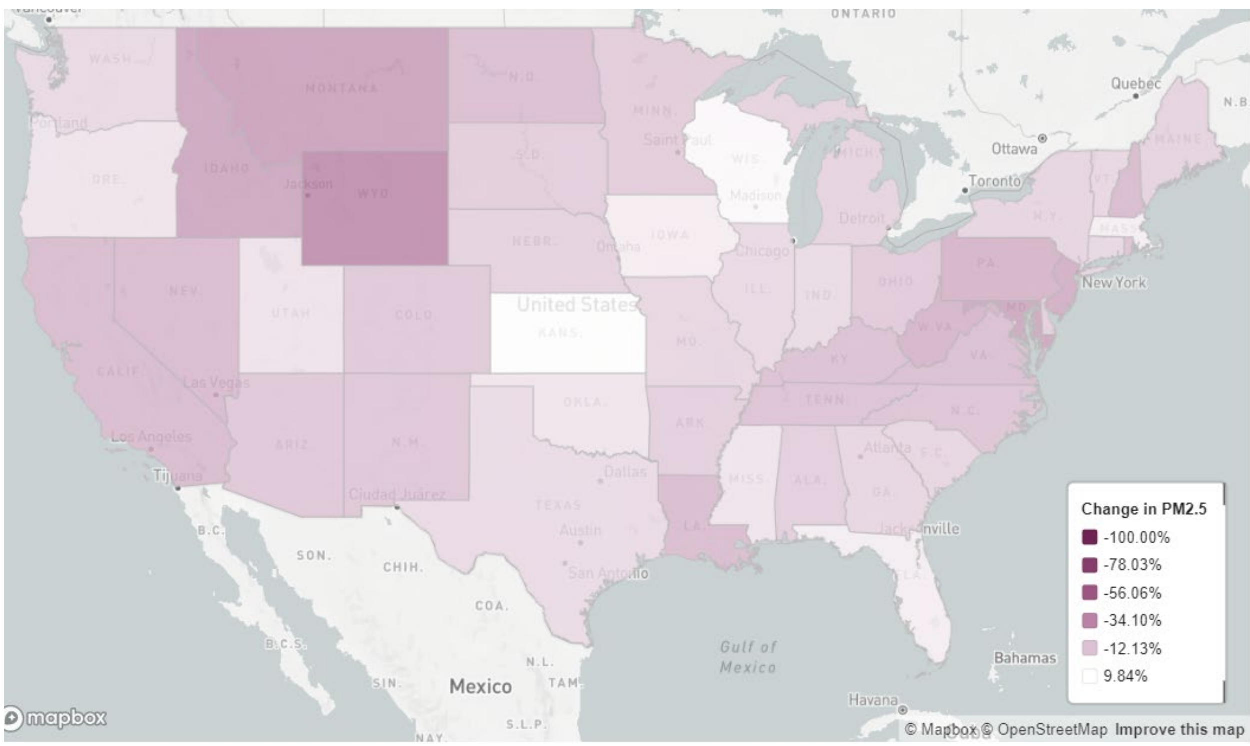

Figure 2. Percentage change in daily average $PM_{2.5}$ concentrations at the state level.

[1] https://www.epa.gov/outdoor-air-quality-data/download-daily-data

Satellite Data Integration

The next step was the recovery of satellite AOD data from the MODIS satellite operated by NASA. The operational algorithms currently generate Level 2 aerosol data with varied spatial resolutions (1, 3, and 10 km) and Level 3 aerosol data at 1 degree. Obtaining, processing, and analyzing higher volumes of data sets at smaller geographical scales are difficult operations that requires advanced computational resources and coding expertise. Therefore, we developed a preprocessed high-spatial-resolution (high-resolution gridded, 0.1 × 0.1 degree) daily and monthly AOD product by integrating two operational MODIS algorithms, namely Deep Blue and Dark Target, based on the literature-referenced processes. AOD data were retrieved for the same time periods as the monitoring data: pre-COVID-19 and post-COVID-19.

The satellite data and the ground-based observations were combined to generate fine-resolution $PM_{2.5}$ concentrations across the contiguous United States. Our approach incorporated many data sources to precisely predict daily $PM_{2.5}$ concentration fields in prior years (2016–2019) and throughout the COVID-19 epidemic (2020). We applied a well-known Gaussian process regression interpolation approach (i.e., ordinary kriging) with a deterministic mean trend surface modeled using a first-order polynomial and ground-based data as the only covariable. Thus, the mean surface concentration was determined by correcting the numerical model simulation with available observations, and the missing grid cells were approximated by interpolation and were added to the mean surface concentration using the kriging method. All model parameters were evaluated daily to provide daily $PM_{2.5}$ concentration fields. Since this was a stochastic model, we could rapidly construct fresh random realizations of the process that retained the key statistics of the estimated field to quantify uncertainty.

This approach has been applied and tested in the literature and has demonstrated high competence in replicating $PM_{2.5}$ concentrations using cross-validation methods. Because the model was calibrated using real data, it could capture $PM_{2.5}$ concentrations both in the usual range and during the COVID-19 epidemic. As demonstrated in Figure 3, the cross-validation mean bias was near zero (0.68 g m-3), and the size of root mean square error (RMSE) was less than 20 percent of the average $PM_{2.5}$ concentrations. Similar bias and decreased RMSE were observed in this study's performance measurements when compared to satellite-based regional-scale studies that used identical metrics (e.g., Bai et al., 2019; Xue et al., 2019).

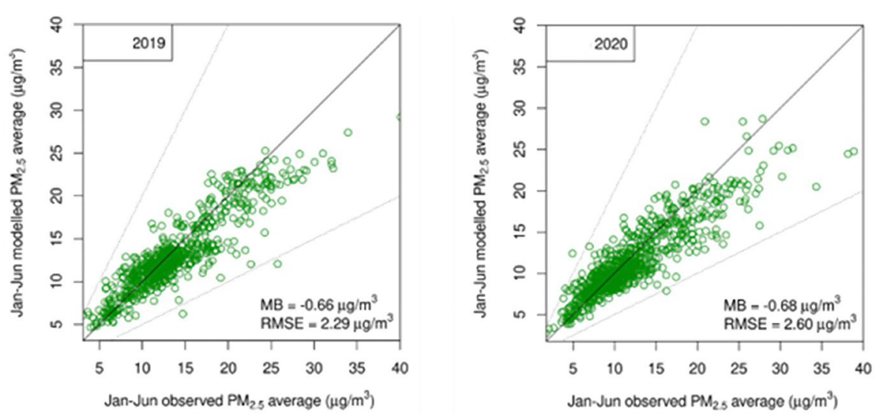

Figure 3. Cross-validation results—$PM_{2.5}$ mean concentrations.

The integrated results were visualized as a Tableau dashboard where the user can filter the results for a particular state or county and explore the grid-level results. The dashboard is available for public use at https://tableau.tamu.edu/t/TTI/views/EffectofCOVID19onAirQuality/EffectofCOVID19LockdownonAirQuality?:showAppBanner=false&:display_count=n&:showVizHome=n&:origin=viz_share_link. The results show a similar trend in reduction of $PM_{2.5}$ during the COVID-19 lockdown period, as Figure 4 shows.

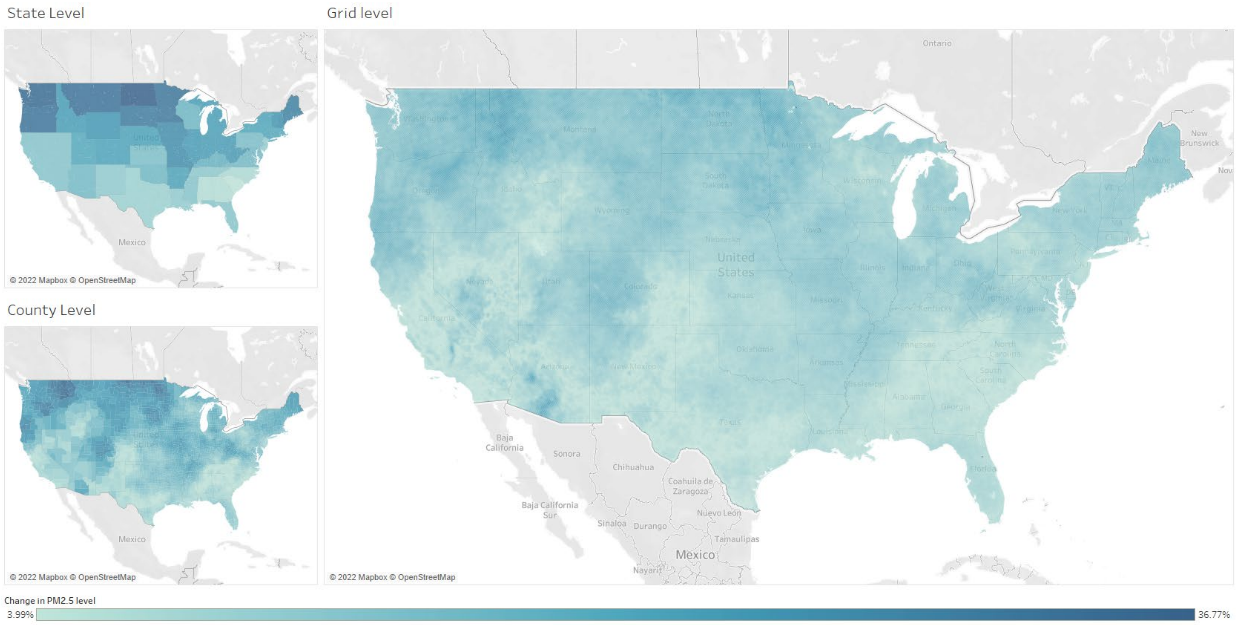

Figure 4. Percentage change in $PM_{2.5}$ concentrations at the state, county, and grid level from the integrated data.

Estimation of $PM_{2.5}$ Mortality

It was anticipated that the enhanced air quality during the lockdown period would reduce short-term premature mortality related to $PM_{2.5}$ concentrations, particularly in the weeks after the implementation of stringent control measures. During the lockdown period in the United States, an estimated maximum of 6489 premature deaths were saved (95 percent confidence interval: 4960–6440) compared to the averages for 2016–2019, as Figure 5 shows.

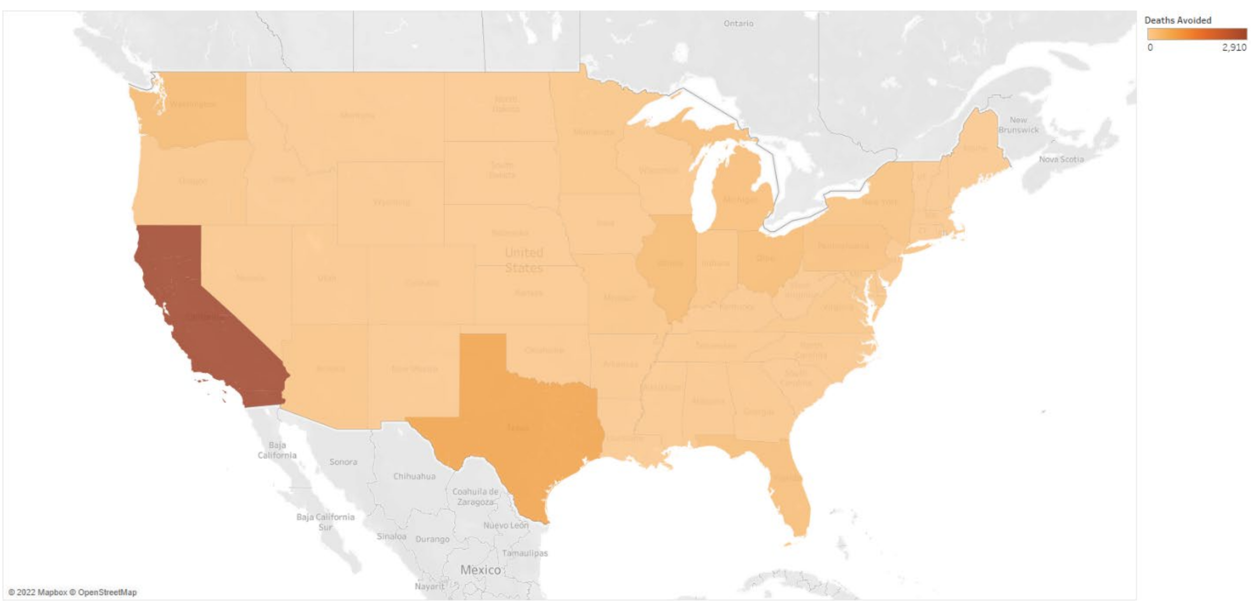

Figure 5. Short-term health impacts of improved air quality and COVID-19 during the lockdown period.

The maximum numbers of deaths avoided were in highly populated states like California (2910) and Texas (740).

Scenarios for Future Economic Recovery

The sensitivity of saved premature deaths in various economic recovery scenarios was examined in different scenarios. We identified the average daily $PM_{2.5}$ values throughout 2016–2019 as usual concentrations and classified the lockdown period (i.e., the time following the outbreak's onset) as March 21 through July 17. We assessed four future economic and emission scenarios:

1. **Immediate restart:** This scenario assumes that the lockdown actions cease in December 2020, resulting in lower annual $PM_{2.5}$ concentrations in 2020 compared to previous years, and a return to usual $PM_{2.5}$ levels in 2021 (i.e., the average between 2016 and 2019). To reduce meteorological fluctuation, we used a 4-year average as a proxy for average concentrations.

2. **Gradual restart:** This scenario is analogous to either a response to/management of a protracted pandemic crisis or lower emissions due to technical advancements and/or changes in working habits and lifestyles (e.g., more remote working and reduced per-capita energy consumption).

3. **Fall/winter outbreak**: This scenario provides for the likelihood of a second coronavirus epidemic in the fall/winter of 2020, which would necessitate similar social isolation measures as in the spring and summer.

4. **Permanent lockdown:** Consideration is given to the extreme case of a permanent lockdown for the entirety of 2021.

Figure 6 shows the number of premature deaths avoided per 100,000 people for the different future economic scenarios.

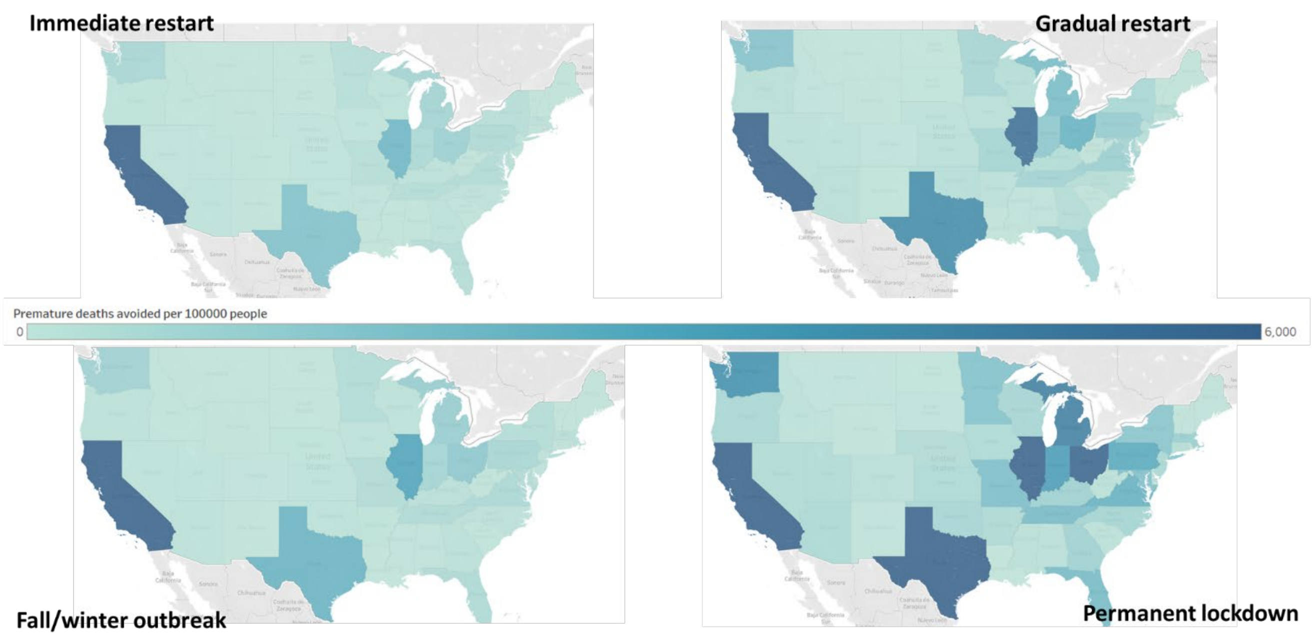

Figure 6. Premature deaths avoided in different states for the future economic scenarios.

Conclusions and Recommendations

As one of the far-reaching repercussions of the ongoing COVID-19 epidemic, the abrupt decline in anthropogenic emissions because of the stringent lockdowns enacted by numerous governments has led to a major improvement in worldwide air quality. In this analysis, we used the control interventions implemented in response to COVID-19 in the United States as a proxy for the reduction in emissions that is achievable within the existing system of environment–human interactions, and we developed several scenarios in which only a fraction of current emissions is controlled over varying time frames. During the shutdown period, we estimate that about 7000 premature deaths due to air pollution were averted in the United States. Overall, even though the ultimate statistics will rely on the future routes to full recovery, this study demonstrates that substantial health benefits are possible with proactive air pollution reduction.

We also anticipate that the true ramifications of these actions in terms of long-term good health effects would be larger than the estimates shown here. Exposure to $PM_{2.5}$ causes a non-negligible increase in the risk of other non-communicable illnesses. Therefore, the number of prevented deaths is likely to be greater than our estimates. In addition, we only considered the health impacts associated with $PM_{2.5}$ concentrations, but considerable reductions in nitrogen oxide emissions might also help to decreasing the death load from respiratory disorders. Other sources of uncertainty in our research include the characterization of lockdown periods and the attribution of avoided mortality to COVID-19-related reductions in activity. We recognize that the dates chosen for the lockdown period are rather arbitrary because of the disparate responses of cities, provinces, and nations to the epidemic. Moreover, the total averted mortality can be partially attributed to other external factors (e.g., favorable meteorology and changes in emission sources and technologies over the past few years), despite the exceptionally low $PM_{2.5}$ concentrations observed after the outbreak indicating the lockdown measures had a substantial impact. Once sector-specific activity data connected to the COVID-19 reaction are revealed, establishing detailed bottom-up emission inventories for the lockdown period might provide more insight into the contribution from diverse causes (e.g., altered emissions and climatic circumstances). Although further research is required to study these elements, it is unlikely that if more data become available, the assumptions made here would affect the overall size of the results.

Outputs, Outcomes, and Impacts

The current study is a novel approach to assess the effect of strict lockdown tactics used to prevent the spread of COVID-19 on air quality and human health on a broad scale. We used observations of fine particulate matter concentrations from over 500 measuring sites in the contiguous United States in 2016–2020 and integrated them with satellite data and the most recent epidemiological studies in order to quantify the short-term and long-term premature deaths avoided during the COVID-19 pandemic. The findings complement the current literature by analyzing the large-scale effects of the various lockout measures on human health in the contiguous United States, providing essential data for policy makers concerned with conserving both environmental quality and public health. Thousands of premature fatalities from air pollution were averted as a consequence of strict lockdown measures.

Our findings show that large improvements in air quality are possible if air pollution control measures are implemented. In addition, because most preexisting respiratory and pulmonary diseases that increase the risk of death from COVID-19 are exacerbated by exposure to fine particulate matter, improving air quality could potentially lower mortality during a viral pandemic. We propose that the difference in risk perception between an environmental catastrophe and a health crisis is due to the spatiotemporal nature of the related mortality rates since society only feels a strong sense of urgency when a disaster is highly localized in space and time. Thus, the reaction to the COVID-19 pandemic provides a unique lesson on the significance of risk communication and the need for political actions to successfully limit air pollution and climate change.

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Research Outputs, Outcomes, and Impacts

A manuscript was developed for the 2023 Transportation Research Board Annual Meeting.

Technology Transfer Outputs, Outcomes, and Impacts

Visualization dashboards to explore the results were uploaded to the CARTEEH data hub and Texas A&M University Tableau server for public access:

- Ground-based data: https://carteehdata.org/library/webapp/effects-of-covid-19-lockd-ab39.
- Combined satellite and ground data: https://tableau.tamu.edu/t/TTI/views/EffectofCOVID19onAirQuality/EffectofCOVID19LockdownonAirQuality?:showAppBanner=false&:display_count=n&:showVizHome=n&:origin=viz_share_link.

Education and Workforce Development Outputs, Outcomes, and Impacts

The project supported one master's student, Sreelekha Gudimala. The student worked on analyzing the combined satellite data to estimate mortality and also helped write the final report.