Determinants of COVID-19 Case Fatality Rate in the United States: Spatial Analysis Over One Year of the Pandemic

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Supplementary Material

INTRODUCTION

The novel coronavirus of 2019 (COVID-19) pandemic continues to spread in the United States and around the world. The United States, as of April 11, 2021, recorded 31.1 million COVID-19 cases and 561,231 deaths.¹ Cases and deaths in the United States continue to account for the largest share of global cases (23%) and global deaths (19%).² Containing the COVID-19 pandemic in the United States was challenging due to virus contagion characteristics, its pathophysiology, and socio-political factors.³ In response to the pandemic, many states initially adopted safety measures such as mask mandates, social distancing and safety measures for operations of certain businesses.⁴⁵ After implementing these restrictive measures including lockdowns, many states rolled back such policies in 2020.⁶ Despite these rollbacks, personal safety measures (mask mandates and social distancing) were continued into the year 2021. However, as of the writing of this study, 14 states in the United States have lifted mask mandates.⁷ Safety measures such as the closure of business establishments, stay-at-home orders, and social distancing mandates severely impacted the economy.⁴ In response to the pandemic, lawmakers passed three stimulus packages and the Coronavirus Aid, Relief, and Economic Security Act (CARES) Act, with additional relief legislation expected.⁸⁹ As of April 11, 2021, Moderna, Pfizer, and Johnson & Johnson vaccines have received emergency use authorization by the
US Food and Drug Administration and are being rolled out in phases. Other biopharmaceutical companies are conducting clinical trials for 60 COVID-19 vaccine candidates. The current vaccine rollout will continue to gain momentum while other COVID-19 vaccines may receive market approval in the near future. Despite this progress, experts recommend that the public follow COVID-19 safety measures due to slow initial rollout, uncertainties surrounding COVID-19 vaccines (virus mutations, duration of immunity, real world effectiveness, vaccine uptake, etc.) and vaccine hesitancy. In summary, the US government and the scientific community has undertaken various measures to address the needs of the population during the COVID-19 pandemic. However, the assessment of the impact of ecological contextual factors such as health behaviors, clinical care and burden, socio-economic, and physical environment-related characteristics on the course of the COVID-19 pandemic is necessary. The contextual understanding from such a study is required to gauge whether lockdown measures worked and to what extent. Moreover, the study also aids in identifying high-risk areas for targeting vaccine distribution. Therefore, having a thorough knowledge of these ecological contextual factors is critical to address the public health and economic challenges and prioritize resources.

Studies so far have generated predictive models for growth in COVID-19 incidence and mortality and estimated the impacts of some community-level factors on COVID-19 incidence and mortality. Millett et al. and Khanijahani et al. focused on assessing the ecological determinants of susceptibility to COVID-19 outcomes among predominantly African American counties, while Fielding-Miller et al. and Peters et al. performed a similar assessment along the rural-urban continuum. Few studies have assessed the spatial determinants of COVID-19 transmission. Recently, Sun et al. assessed the relationship between various county-level determinants and COVID-19 incidence while Andersen et al. also identified high prevalence clusters. These studies evaluated the incidence and prevalence during the initial phase of the pandemic and limited the analysis to a few county-level and policy-related factors.

Incidence and mortality were critical outcomes in shaping the initial pandemic response to reduce the contagion. However, to reduce fatalities in the current stage of the pandemic, an increasing focus is placed on mitigation strategies such as increasing vaccination rates and continuing safety precautions such as social distancing and mask use. Therefore, COVID-19 case-fatality rate (CFR) is a useful outcome measure in the current stage of the pandemic. CFR, being less susceptible to testing and reporting biases, also reflects the disease severity. In a study led by author Cao, country-level demographic and socioeconomic characteristics on COVID-19 CFR were presented. However, to our knowledge, in the United States, no study has estimated the effect of county-level ecological factors, including policy-related factors, on COVID-19 CFR.

The objective of the current study was to assess the impact of county-level ecological factors, using spatial econometric analysis, on the COVID-19 CFR over one year of the pandemic.

**METHODS**

**Data source and study design**

The current study used county-level COVID-19 confirmed cases and deaths data from the New York Times repository extracted as of February 27, 2021, and included data up until that date. The study used county-level characteristics from 2020 County Health Rankings data and 2018-2019 Area Health Resource File data. State-level stringency index, percent positive for COVID-19, and social distancing score were obtained from Oxford COVID-19 government response tracker, the COVID Tracking Project, and Unacast, respectively. Alaska and Hawaii counties were excluded from the analysis. The US counties ESRI Shapefile was obtained from the US Census Bureau. The study employed a cross-sectional ecological study design to assess the association between county-level characteristics on the cumulative COVID-19 CFR.

**Outcomes**

The county-level US COVID-19 cumulative confirmed cases and deaths data from the New York Times repository was extracted as of February 27, 2021, data up until that date was included. The COVID-19 cumulative CFR was operationally defined as a ratio of the cumulative COVID-19 deaths by cumulative COVID-19 cases. The current analysis used CFR as the outcome of interest because it reflects the disease severity, treatment effectiveness, and responsiveness of the health-care system. Additionally, since the measure is a ratio, compared to incidence rate or mortality rate, the CFR is less sensitive to differences in testing rates across regions.

**Covariates**

The covariates selected within the model to predict the county-level CFR were adapted from the County Health Ranking Framework (CHR.F). The framework categorizes health factors into four sub-categories, namely health behaviors, clinical care, socioeconomic factors, and physical environment (Figure 1). Each of the sub-categories is further divided into individual factors. The CHR.F model was used in the current analysis because it provides a well-established theoretical framework for studying ecological determinants of health outcomes. The current analysis augmented the CHR.F by including additional covariates based on additional demographic measures from county health ranking, and prior ecological studies on COVID-19. Firstly, an additional sub-category of “clinical burden” was added, which included measures such as low-birth weight, percent diabetes prevalence, and premature age-adjusted mortality. Secondly, nursing home beds, long-term care beds, and total hospital beds were added to the clinical care sub-category. Thirdly, population characteristics such as rurality, poverty, age distribution, population, population density, supplemental nutritional assistance program (SNAP) eligibility, and percentage of workforce in various occupational categories were added to the social and economic factors sub-category. Additionally, physical environmental factors such as percentage of workers using public transport were added to the respective sub-category. Finally, COVID-19 related factors were added to the model, which included month of first infection in the county, positivity rate for COVID-19 at the state-level, social distancing score, and stringency index. The final list of potential county-level covariates and corresponding rationale are described in Table 1. Although the CHR.F model assigns weight to each of the components, they were not utilized in the current analysis as no composite rank score was calculated.

**Statistical Analyses**

Descriptive univariate statistics of the weighted county-level characteristics were generated. Firstly, all covariates in Table 1, selected as potential covariates, underwent a two-step covariate selection process. In the first step, multicollinearity was assessed and factors with variance inflation factor > 7 were excluded. In the second step, Pearson correlation between remaining factors was tested (Supplemental Table 1) and factors with correlation greater than 0.7 were excluded. All remaining factors were used in regression analysis. Secondly, the presence of spatial correlation was confirmed by performing Moran’s I test for spatial correlation. Two island counties were excluded because spatial regression analysis necessitates that the data contains no island
Based on prior research, the LeSage and Pace method was used to determine the best fit spatial regression model. A first-order queen spatial weight matrix was employed for all spatial models. The queen matrix defines neighbor relationships if the counties either share a border or a vertex. All analysis was performed in RStudio (R) v 4.0.3 (Boston, Massachusetts) and QGIS v 3.16.0 (Berne, Switzerland).

RESULTS

The final analysis included data from 3101 counties from the mainland United States. Between January 20, 2020 to February 27, 2021, the population-weighted COVID-19 CFR for the mainland United States was 1.82%. Table 2 demonstrates the descriptive statistics of the COVID-19 CFR and county-level determinants, namely, COVID-19 policy-related factors, health behaviors, clinical burden, clinical care, socio-economic, and physical environment factors. Some 2097 counties reported their first case in March 2020. The percent positivity for COVID-19 was 9%. The mean social distance score and stringency index at the county-level was 1.75 and 49.14, respectively. The proportion of adult smokers, those with physical inactivity, obesity, and Medicare enrollees who were administered influenza vaccines were 15%, 23%, 29%, and 46%, respectively. At the county-level, the average ratio of population to primary care physicians was 74 and the average preventable hospitalization rate was 4545 per 10000 Medicare enrollees. Premature age-adjusted mortality was 342 per 100000. Among socio-economic factors, the proportion of the workforce in education/health-care/social assistance field, construction, and manufacturing comprised 23%, 7%, and 10% of the population, respectively. Additionally, unemployment was 4%, 12% of adults were uninsured, the mean income inequality ratio was 5 and adults with some college education made up 65% of the population. About 13% were African Americans, 18% Hispanics, 1% Native Americans, 51% females, 33% of the children lived in single parent households, and 4% of the population was not proficient in English. The percentage of the population older than 65 years and less than 18 years were 16% and 22%, respectively. On average, 19% of counties were rural, the homeownership rate was 64%, 18% used public transportation and 18% of households had severe housing problems. Lastly, population density/100 sq. miles was found to be 2067.

Figure 2 presents the spatial distribution (quintiles) of COVID-19 CFR. In the West, Washington’s Spokane area and Nevada’s Las Vegas area had high COVID-19 CFR. High COVID-19 CFR clusters were found in border counties of Arizona’s Phoenix area and in New Mexico. In Montana, all major cities such as Helena, Butte, and Billings and along the border of Wyoming (specifically near Yellow Stone National Park) had high COVID-19 CFR. In the Midwestern region, barring the high COVID-19 CFR clusters in Michigan’s Upper Peninsula area, there were many scattered counties with high CFR. The Deep South states of Mississippi, Louisiana, Tennessee, central Alabama, and Arkansas had clusters of high COVID-19 CFR. The Texas panhandle region, the Corpus Christie, Texas, area and the area along the US-Mexico border had clusters of high COVID-19 CFR. In the Northeastern region, high COVID-19 CFR clusters were found between the large parts of Pennsylvania and New Jersey, and in the Boston, Massachusetts, area. Additionally, in Maine, clusters of high COVID-19 CFR were found around Acadia National Park and the northeastern parts of the state.

Figure 1: Theoretical Framework Based on the County Health Rankings Model To Establish a Relationship Between COVID-19 Case Fatality Rate and County-level Ecological Factors

| Health Outcomes (COVID-19 CFR) | Health Behaviors | Physical Environment |
|--------------------------------|------------------|----------------------|
|                                |                  |                      |
|                                |                  |                      |

Abbreviations: CFR, Case fatality rate; SNAP, supplemental nutritional assistance program.

\(^{\text{\textdagger}}\) indicates that the data was obtained from additional resources and supplementary files of the County Health Rankings,\(^{\text{\textdagger}}\); * indicates that the data was obtained from sources other than those in the County Health Rankings data.
Table 1: Ecological Factors Used in the Analysis: Source Definitions and Modifications

| Factors                                                                 | Definitions & Rationale                                                                                                                                                                                                                           | Source                                                                                                                   |
|------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|
| Calendar Month of the First Reported Case in the State                 | Generated as the month when the first COVID-19 case was reported in the county. Based on the frequency distribution the following categories were created: January, February, March, April, May, and June to December. Month of first reported case has been used in previous studies. Earlier studies have included this variable due to its significant impact on the cumulative cases and deaths during the early phases of the pandemic. |
| Percent Positive for COVID-19*                                         | This factor was defined as the proportion of all COVID-19 tests performed that are positive. Positivity rate = (positive tests)/(total tests) x 100%. Percent positivity rate is a proxy measure for extent of under/over testing and has been included to control for impact of geographic differences in testing rates. |
| Social Distance Score                                                   | It is defined as the average numerical score based on the following three metrics:  
  - Change in average distance traveled compared to a pre-COVID-19 period.  
  - Change in visitation to non-essential venues compared to a pre-COVID-19 period.  
  - Probability that two devices were in the same place at the same time.  
  During the initial phases of the pandemic, social distances scores were found to be associated with lower COVID-19 mortality. |
| Stringency Index                                                       | Composite measure based on 9 response indicators, including school closures, workplace closures, testing policy and travel bans, rescaled to a value from 0 to 100 (100=strictest response). Stringency index has been previously used in ecological research on COVID-19 CFR. |
| Percent Adult Smokers                                                  | Percentage of adults who are current smokers.                                                                                                                                          | CHRF Data                                                                                                                |
| Percent of Poor or Fair Health                                         | Percentage of adults reporting fair or poor health (age-adjusted).                                                                                                                                                                             |
| Percent Low Birthweight                                                | Percentage of live births with low birthweight (< 2500 grams).                                                                                                                        | CHRF Data                                                                                                                |
| Teen Birth Rate                                                        | Births per 1000 females ages 15-19                                                                                                                                                   | CHRF Data                                                                                                                |
| Percent Adult Obesity                                                  | Percentage of the adult population (age 20 and older) who report a body mass index greater than or equal to 30 kg/m².                                                            | CHRF Data                                                                                                                |
| Percent Excessive Drinking                                             | Percentage of adults reporting binge or heavy drinking.                                                                                                                              | CHRF Data                                                                                                                |
| Percent Flu Vaccine                                                    | Percentage of fee-for-service Medicare enrollees who had an annual flu vaccination.                                                                                                                                                           |
| Percent with Annual Mammogram                                         | Percentage of female Medicare enrollees having an annual mammogram (age 65-74).                                                                                                                                                               |
| Percent Physical Inactivity                                            | Percentage of adults age 20 and over reporting no leisure-time physical activity.                                                                                                                                                           |
| Income Inequality Ratio                                                | Ratio of household income at the 80th percentile to income at the 20th percentile.                                                                                                                                                              |
| Primary Care Physicians Rate (log)*                                   | Log of ratio of population to primary care physicians.                                                                                                                               | CHRF Data                                                                                                                |
| Preventable Hospitalization Rate (log)*                               | Rate of hospital stays for ambulatory-care sensitive conditions per 100000 Medicare enrollees.                                                                                           |
| Percent Educated at Some College                                       | Percentage of adults aged 25-44 with some post-secondary education.                                                                                                                     | CHRF Data                                                                                                                |
| Percent Unemployment                                                   | Number of people aged 16 years and above unemployed and looking for work.                                                                                                               | CHRF Data                                                                                                                |
| Percent Single Parent                                                  | Percentage of children who live in single-parent households.                                                                                                                          | CHRF Data                                                                                                                |
| Social Association Rate                                                | Number of membership associations per 10000 population.                                                                                                                             | CHRF Data                                                                                                                |
| Pollution Level: PM 2.5                                                | Average daily density of fine particulate matter in micrograms per cubic meter (PM2.5).                                                                                                 |
| Percent Severe Housing Problem                                         | Percentage of households with at least 1 of 4 housing problems: overcrowding, high housing costs, lack of kitchen facilities, or lack of plumbing facilities.                                      |
| Percent Homeownership                                                  | Percentage of occupied housing units that are owned.                                                                                                                                  | CHRF Data                                                                                                                |
| Factors                                      | Definitions & Rationale                                                                 | Source                                      |
|---------------------------------------------|----------------------------------------------------------------------------------------|---------------------------------------------|
| Percent Uninsured Adult                     | Percentage of adults under age 65 without health insurance.                            | CHRF (Additional Measures)                 |
| Premature Age-adjusted Mortality            | Number of deaths among residents under age 75 per 100 000 population (age-adjusted).  |                                             |
| Median Household Income (in Thousands)      | The income where half of households in a county earn more and half of households earn less. |                                             |
| Percent Over 65                             | Percentage of population aged 65 and older.                                             |                                             |
| Percent Less Than 18                        | Percentage of population below 18 years of age.                                         |                                             |
| Percent Black                               | Percentage of population who are non-Hispanic African American.                         |                                             |
| Percent Native American                     | Percentage of population who are American Indian or Alaska Native.                      |                                             |
| Percent Hispanic                            | Percentage of population who are Hispanic.                                              |                                             |
| Percent Female                              | Percentage of population who are female.                                                |                                             |
| Segregation Index: White/Non-White          | Index of dissimilarity where higher values indicate greater residential segregation between non-White and White county residents. |                                             |
| Percent Rural                               | Percentage of population living in a rural area.                                        |                                             |
| Percent Not Proficient in English           | Percentage of population who are not proficient in English.                             |                                             |
| Percent Diabetics                           | Percentage of adults aged 20 and above with diagnosed diabetes.                         |                                             |
| Percent with Food Insecurity                | Percentage of population who lack adequate access to food.                              |                                             |
| Mental Health Provider Rate                 | Mental health providers per 100 000 population.                                         |                                             |
| Chlamydia Rate (Log)                        | Chlamydia cases per 100 000 population.                                                |                                             |
| Percent SNAP Recipients                     | Percentage of the population on food stamps or SNAP.                                    | 2019-2020 AHRF                             |
| Percent Public Transportation               | Percentage of the population using public transportation.                               |                                             |
| Percent of Workforce in Education, Health-care and Social Assistance Field | Percentage of the population in the occupation of education/health-care/social assistance. |                                             |
| Percent of Workforce in Construction        | Percentage of the population who work in construction.                                  |                                             |
| Percent of Workforce in Manufacturing       | Percentage of the population who are manufacturing workers.                             |                                             |
| Percent Poverty                             | Percentage of the population below poverty level.                                       |                                             |
| Hospital Bed Rates (log)                    | Number of beds regularly maintained (set up and staffed for use) for inpatients.         |                                             |
| Nursing Home Beds                           | Number of nursing home unit beds in hospitals.                                          |                                             |
| Long-term Care Beds (log)                   | Number of long-term care beds in hospitals.                                             |                                             |
| Population                                  | Resident population.                                                                    |                                             |
| Population Density (log)                    | Persons per 100 square mile area.                                                      |                                             |

Abbreviations: AHRF, Area Health Resource Files; CHRF, County Health Ranking Framework; SNAP, supplemental nutritional assistance program.

*These variables are derived or converted for use within the regression model.
Table 2: Descriptive Statistics of Ecological Factors (N=3101)

| Ecological Factors | Overall | VIF |
|--------------------|---------|-----|
| Sample size        | 326 Million (population of 3101 counties) |     |
| Mean               |         |     |
| Cases              | 110257.75 | 214169.92 |
| Deaths             | 1991.70  | 3956.85  |
| Case fatality rate*| 1.82     | 0.82     |
| **Census Region [n, %]** ^ |         |     |
| Northeast          | 217.00   | 7.00    |
| Midwest            | 1055.00  | 33.90   |
| South              | 1422.00  | 45.80   |
| West               | 414.00   | 13.30   |
| **COVID-19 Policy-related Factors** ^ |         |     |
| Calendar Month of the First Reported Case in the State [n, %] | n | % |
| January            | 6.00     | 0.20     |
| February           | 16.00    | 0.50     |
| March              | 2097.00  | 67.50    | 2.71 |
| April              | 692.00   | 22.30    |
| May                | 133.00   | 4.30     |
| June to December   | 164.00   | 5.30     |
| % Positive for COVID-19 | 9.30 | 4.10 | 1.99 |
| Social Distance Score | 1.75  | 0.63 | 3.30 |
| Stringency Index   | 49.14    | 11.21    | 2.03 |
| **Health Behaviors** |         |     |
| % Adult Smoking    | 15.31    | 3.43     | 8.85 |
| Food Insecurity    | 7.83     | 0.85     | 3.20 |
| Chlamydia Rate*    | 520.05   | 236.40   | 3.09 |
| % Fair or Poor Health | 16.74 | 3.83   | 15.65 |
| Teen Birth Rate    | 22.81    | 11.11    | 5.11 |
| % Physical Inactivity | 23.31 | 5.37  | 2.50 |
| % Excessive Drinking | 18.76 | 2.80 | 3.09 |
| % Adult Obesity    | 29.06    | 5.53     | 2.06 |
| **Clinical Burden** |         |     |
| % Low Birthweight  | 8.07     | 1.42     | 3.07 |
| % Diabetic         | 10.25    | 2.77     | 1.91 |
| Premature Age Adjusted Mortality* | 341.61 | 93.01 | 4.95 |
| **Clinical Care** |         |     |
| Primary Care Physicians Rate* | 75.41 | 30.36 | 2.17 |
| Preventable Hospitalization Rate | 4545.01 | 1270.42 | 1.63 |
| Hospital Beds*     | 3200.65  | 5035.30  | 1.84 |
| Nursing Home Beds* | 77.79    | 187.85   | 1.13 |
| Long-term Care Beds* | 128.89 | 260.27 | 1.28 |
| Mental Health Provider Rate* | 247.42 | 161.55 | 2.09 |
| % With Annual Mammogram | 41.15 | 6.19 | 2.29 |
| % Influenza Vaccinations | 46.11 | 6.91 | 2.05 |
| **Socio-economic Factors** |         |     |
| % SNAP Recipients  | 12.43    | 5.92     | 7.25 |
| % of Workforce in Education/Health-care/Social Assistance Field | 23.12 | 3.92 | 1.92 |
| % of Workforce in Construction | 6.52 | 1.81 | 1.53 |
| % of Workforce in Manufacturing | 10.23 | 5.40 | 2.30 |

Continued
Table 2: Descriptive Statistics of Ecological Factors (N=3101)

|                                | Mean 1  | Mean 2  | SD    |
|--------------------------------|---------|---------|-------|
| Income Inequality Ratio        | 4.72    | 0.78    | 2.24  |
| % Adults with Some College Education | 65.33  | 9.81    | 3.97  |
| % Unemployment                 | 3.96    | 1.12    | 2.42  |
| % Children in Single-parent Households | 33.15  | 8.68    | 3.67  |
| Social Association Rate*       | 9.01    | 3.60    | 1.67  |
| % Uninsured Adults             | 10.25   | 4.81    | 3.40  |
| Median Income*                 | US$65,045.85 | US$17,989.94 | 11.00 |
| % 65 Years Old and Over        | 16.02   | 4.04    | 5.78  |
| % Less Than 18 Years of Age    | 22.44   | 2.94    | 4.70  |
| % African American             | 12.55   | 12.56   | 5.19  |
| % Native Americans             | 1.24    | 3.18    | 2.64  |
| % Hispanic                     | 18.35   | 17.18   | 7.80  |
| % Female                       | 50.76   | 1.23    | 2.70  |
| % Not Proficient in English    | 4.41    | 4.38    | 4.17  |
| Residential Segregation Non-White/White | 37.03  | 11.27   | 1.47  |
| % Poverty                      | 13.05   | 4.82    | 11.57 |

**Physical Environment**

|                                | Mean 1  | Mean 2  | SD    |
|--------------------------------|---------|---------|-------|
| Air Pollution-particulate Matter (2.5) | 10.08  | 2.11    | 2.94  |
| % Severe Housing Problem       | 18.09   | 5.85    | 2.82  |
| % Rural                       | 18.68   | 24.06   | 4.58  |
| % Homeownership                | 63.77   | 10.82   | 3.21  |
| % Public Transportation        | 18.24   | 3.95    | 1.31  |
| Population*                    | 1,172,722.28 | 1,940,307.84 | 8.34  |
| Population Density per 100 sq. miles* | 2067.26 | 6497.01 | 9.12  |

Abbreviations: SD, Standard Deviation; SNAP, supplemental nutritional assistance program; VIF, Variance Inflation Factor.

* Cumulative case fatality rate calculated as of February 27, 2021.
* VIF was calculated on the log transformed values.
^ Unweighted estimates, as this represents the number of counties.

Figure 2: Spatial Distribution of the Cumulative COVID-19 Case Fatality Rate by Quintiles as of February 27, 2021
The first step in the factor selection process identified and excluded percent adult smokers, percent fair/poor health, log population density, log population, percent under poverty, median income, percent eligible for SNAP benefits due to multicollinearity, which is shown in Table 2. Similarly, percent smokers, teen birth rate, percent SNAP eligible, log population, log population density, percent speaking language other than English were excluded based on high correlation with other factors (Supplemental Table 1). The presence of spatial autocorrelation was confirmed based on a significant Moran's I test statistic (Moran's I=0.256, P-value<0.001). The LeSage and Pace method identified that Spatial Durbin Model (SDM) was a better fit to the data compared with other spatial regression models. The significant Rho parameter of the SDM model indicates that (Rho=0.447, P-value<0.001), a 1% increase in a neighboring county's CFR, also results in 0.447% increase in CFR rate in the particular county.

The multivariable SDM results are presented in Table 3. The factors significantly associated with CFR included percent positive for COVID-19 (β=0.059), stringency index (β=0.015), log nursing home beds (β=0.005), log long-term care beds (β=0.008), percent workforce in construction (β=0.019), log premature age-adjusted mortality (β=0.711), income inequality ratio (β=0.076), percent population 65 years and older (β=0.055), and percent severe housing problem (β=-0.023). Additionally, the spatial lag term for factors such as percent positive for COVID-19 (lag β=-0.048), stringency index (lag β=-0.017), social distancing score (lag β=-0.136), adult obesity (lag β=-0.026), log long-term care bed (lag β=-0.025), log mental health provider rate (lag β=-0.080), percent workforce in education/health-care/social assistance (lag β=-0.018), log social association rate (lag β=-0.038), percent female (lag β=-0.057), and percent rurality (lag β>=0.005) were also associated with COVID-19 CFR.

As the β from SDM are not directly interpretable, the estimates from the SDM were decomposed into direct and indirect effects using the Impacts command from spdep package as shown in Table 3. Several factors had significant direct impact on the county's COVID-19 CFR. Firstly, two of the COVID-19 related factors, namely, percent positive for COVID-19 (direct impact: 0.057% point), and stringency index (direct impact: 0.014% point) were positively associated with COVID-19 CFR in that county. Secondly, among health behavior related factors, percent adult obesity (direct impact: -0.013% point) was negatively associated with COVID-19 CFR. Thirdly, among the clinical burden and clinical care related factors, percent diabetics (direct impact: 0.011% point), log premature age-adjusted mortality (direct impact: 0.702% point), and log long-term care beds (direct impact: 0.010% point) were positively associated with COVID-19 CFR, while log nursing home beds (direct impact: -0.005% point) was negatively associated with COVID-19 CFR.

Several socio-economic factors, importantly, income inequality (direct impact: 0.078% point), log social association rate (direct impact: 0.014% point), and percentage African Americans (direct impact: 0.007% point) were positively associated with COVID-19 CFR, while percentage workforce in construction (direct impact: -0.024% point) and percentage adults with some college education (direct impact: -0.004% point) were negatively associated with COVID-19 CFR.

The decomposition estimates also demonstrated strong indirect effects of spatial lag terms indicating externality associated with ecological factors from surrounding counties on COVID-19 CFR. The directionality of the direct and indirect associations was similar for the majority of the factors. However, some of the factors demonstrated divergent direct and indirect effects on COVID-19 CFR. For illustration, among COVID-19 policy-related factors, both percent positive for COVID-19 (direct: 0.057% point; indirect impact: -0.035% point) and stringency index (direct impact: 0.014% point; indirect impact: -0.017% point) of neighboring counties were negatively associated with COVID-19 CFR in a given county. Interestingly, the magnitude of the indirect associations were larger than the direct associations for the majority of the factors, except for percent 65 years old and over (direct: 0.055% point; indirect: 0.024% point), and percent severe housing problem (direct: -0.024% point; indirect: -0.009% point).

It is noteworthy that for some of the factors, while either the direct or indirect impacts were insignificant, the total impact was found to be significant: for example, food insecurity (total impact: 0.160), log of mental health provider rate (total impact: -0.146% point), percent workforce in education/health-care/social assistance field (total impact: 0.045% point), percent uninsured adults (total impact: 0.028% point), percent 65 years old and over (total impact: 0.079% point), residential segregation non-White/White (total impact: 0.015% point), and percent rural (total impact: 0.007% point). For percent excessive drinking factor, although the direct and indirect impacts were found to be insignificant, the overall total impact (0.043% point) was significant.
Table 3: Spatial Durbin Model for the Case Fatality Rates as of February 27, 2021 Using NYT, AHRF, and CHRF Datasets

| Ecological Factors | Spatial Durbin Model | Decomposition Estimates |
|--------------------|----------------------|-------------------------|
|                    | Estimate | Lag Estimate | Direct | Indirect | Total |
| **COVID-19 Policy-related Factors** |          |              |        |          |       |
| Calendar Month of the First Reported Case in the State [n, %]* |          |              |        |          |       |
| January | -0.253 | -0.288 | -0.253 | -0.673 | -0.927 |
| February | -0.375 | 0.380 | -0.345 | 0.333 | -0.011 |
| March | -0.407 | 0.231 | -0.396 | 0.048 | -0.348 |
| April | -0.368 | 0.026 | -0.378 | -0.257 | -0.635 |
| May | -0.586 | 0.845 | -0.521 | 0.955 | 0.434 |
| June to December |           |              |        |          |       |
| % Positive for COVID-19 | 0.059 *** | -0.048 *** | 0.057 *** | -0.035 ** | 0.022 ** |
| Social Distance Score | 0.062 | -0.136 * | 0.056 | -0.185 | -0.129 |
| Stringency Index | 0.015 ** | -0.017 ** | 0.014 ** | -0.017 ** | -0.003 |
| **Health Behaviors** |          |              |        |          |       |
| Food Insecurity | 0.000 | 0.086 | 0.011 | 0.148 * | 0.160 * |
| Chlamydia Rate (log) | -0.034 | 0.173 | -0.024 | 0.260 | 0.236 |
| % Physical Inactivity | 0.002 | -0.009 | 0.002 | -0.013 | -0.011 |
| % Excessive Drinking | -0.002 | 0.025 | 0.000 | 0.043 | 0.043* |
| % Adult Obesity | -0.009 * | -0.026 * | -0.013 ** | -0.054 *** | -0.066 *** |
| **Clinical Burden** |          |              |        |          |       |
| % Low Birthweight | -0.022 | 0.002 | -0.023 | -0.008 | -0.031 |
| % Diabetic | 0.008 | 0.022 | 0.011 * | 0.044 * | 0.055 * |
| Premature Age Adjusted Mortality (log) | 0.711 *** | -0.469 * | 0.702 *** | -0.234 | 0.467 |
| **Clinical Care** |          |              |        |          |       |
| Primary Care Physicians Rate (log) | -0.003 | -0.005 | -0.003 | -0.009 | -0.011 |
| Preventable Hospitalization Rate | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Hospital Beds (log) | 0.003 | 0.001 | 0.003 | 0.003 | 0.006 |
| Nursing Home Beds | -0.005 * | -0.001 | -0.005 * | -0.006 | -0.011 |
| Long-term Care Beds (log) | 0.008 * | 0.025 *** | 0.010 ** | 0.048 *** | 0.058 *** |
| Mental Health Provider Rate (log) | -0.001 | -0.080 *** | -0.010 | -0.136 *** | -0.146 *** |
| % With Annual Mammogram | -0.001 | -0.003 | -0.001 | -0.004 | -0.005 |
| % Influenza Vaccinations^ | -0.004 | 0.003 | -0.004 | 0.002 | -0.002 |
| **Socio-economic Factors** |          |              |        |          |       |
| % of Workforce in Education/Health-care/Social Assistance Field | 0.006 | 0.018 * | 0.009 | 0.036 ** | 0.045 ** |
| % of Workforce in Construction | -0.019 * | -0.027 | -0.024 ** | -0.063 * | -0.086 ** |
| % of Workforce in Manufacturing | 0.001 | 0.006 | 0.002 | 0.011 | 0.012 |
| Income Inequality Ratio | 0.076 * | -0.063 | 0.078 ** | -0.056 | 0.022 |
| % Adults with Some College Education | -0.004 | -0.001 | -0.004 ** | -0.005 * | -0.009 ** |
| % Unemployment | 0.039 | 0.040 | 0.045 | 0.096 | 0.141 |
| % Children in Single-parent Households | 0.003 | 0.004 | 0.003 | 0.008 | 0.011 |
| Social Association Rate (log) | 0.011 | 0.038 ** | 0.014 ** | 0.073 ** | 0.087 ** |
| % Uninsured Adults | 0.014 | 0.001 | 0.015 | 0.014 | 0.028 * |
| % 65 Years Old and Over | 0.055 *** | -0.009 | 0.055 *** | 0.024 | 0.079 ** |
| % Less Than 18 Years of Age | 0.016 | 0.020 | 0.018 | 0.044 |       |
| % African American | 0.006 | 0.002 | 0.007 * | 0.009 | 0.016 * |
| % Native Americans | -0.007 | 0.000 | -0.007 | -0.006 | -0.013 |
| % Hispanic | -0.003 | 0.008 | -0.002 | 0.011 * | 0.009 |
| % Female | 0.018 | -0.057 ** | 0.013 | -0.081* | -0.068 |
| Residential Segregation Non-White/White | 0.001 | 0.007 * | 0.002 | 0.013 ** | 0.015 ** |

*Continued*
Spatial Durbin Model found that greater proportions of racial minorities (Hispanics and African Americans) and found results similar to the present study.

CONCLUSION

The findings of this study are more insightful than the mere coronavirus count meters and data visualizations that depict the spread of the COVID-19 pandemic. The current spatial models incorporated a comprehensive list of factors to ensure that the results, when parsed, offer a multi-faceted explanatory power. For illustration, these models helped identify factors including COVID-19 policy-related factors (stringency index, social distancing score, and percent positive), health behaviors (example: excessive drinking), clinical burden (example: percent diabetic, premature age-adjusted mortality), clinical care (example: mental health provider rates), socio-economic factors (example: race/ethnicity, income inequality, segregation index, education, workforce composition), and physical environment (example: rurality) as some of the important determinants of the geographic disparities in COVID-19 CFR. This study highlights the plausible effect of one's residential location, vicinity, local state policy...
and the connectivity to the neighboring counties on COVID-19 CFR. The United States is facing the next set of challenges in limiting fatalities and COVID-19 mutations, while undertaking mass immunization for COVID-19. At this crucial juncture, the current study findings provide guidance on identifying areas at greater risk of COVID-19 CFR.

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