Disaster Medicine and Public Health Preparedness

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SARS-CoV-2 Transmission Potential and Policy Changes in South Carolina, February 2020 – January 2021

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Original Research

Cite this article: Davies MR, Hua X, Jacobs TD, *et al*. SARS-CoV-2 transmission potential and policy changes in South Carolina, February 2020 – January 2021. *Disaster Med Public Health Prep*. **17**(e276), 1–10. doi: https://doi.org/10.1017/dmp.2022.212.

Keywords:
COVID-19; epidemiology; nonpharmaceutical interventions; mask mandate; reproduction number

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Abstract

Introduction: We aimed to examine how public health policies influenced the dynamics of coronavirus disease 2019 (COVID-19) time-varying reproductive number (R_t) in South Carolina from February 26, 2020, to January 1, 2021.

Methods: COVID-19 case series (March 6, 2020, to January 10, 2021) were shifted by 9 d to approximate the infection date. We analyzed the effects of state and county policies on R_t using EpiEstim. We performed linear regression to evaluate if per-capita cumulative case count varies across counties with different population size.

Results: R_t shifted from 2-3 in March to <1 during April and May. R_t rose over the summer and stayed between 1.4 and 0.7. The introduction of statewide mask mandates was associated with a decline in R_t (−15.3%; 95% CrI, −13.6%, −16.8%), and school re-opening, an increase by 12.3% (95% CrI, 10.1%, 14.4%). Less densely populated counties had higher attack rates ($P < 0.0001$).

Conclusions: The R_t dynamics over time indicated that public health interventions substantially slowed COVID-19 transmission in South Carolina, while their relaxation may have promoted further transmission. Policies encouraging people to stay home, such as closing nonessential businesses, were associated with R_t reduction, while policies that encouraged more movement, such as re-opening schools, were associated with R_t increase.

In late December 2019, a novel virus was reported in Wuhan, China. By January 2020, this virus had been identified as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the causative agent of coronavirus disease 2019 (COVID-19).[1] The disease was first reported in the United States in January 2020.[2]

With an estimated population of 5,190,705, South Carolina is in the southeastern United States, along the Atlantic coast, and shares borders with North Carolina and Georgia.[3] South Carolina reported the first case of COVID-19 in the state on March 6, 2020. On March 13, 2020, the Governor of South Carolina declared a State of Emergency.[4] By April 2, 2020, every county in South Carolina had reported at least 1 case. Here, we report on cases through January 10, 2021, by which point 361,254 cases had been reported, of whom 5811 died.

Central to infectious disease epidemiology is the concept of the reproduction number (R_0) – the average number of secondary cases that a primary case can infect absent any public health intervention in a completely susceptible population.[5] Before the appearance of the highly transmissible Delta (B.1.617.2) variant, the R_0 for COVID-19 was estimated to lie between 2.2,[6] and 4.4.[7] In contrast, the time-varying reproduction number (R_t) describes the transmission potential at a given timepoint as behavior changes and as public health interventions are implemented.[8] This makes R_t a better measure of disease spread over time as populations put interventions into effect.[9,10] Public health policies regarding nonpharmaceutical interventions (NPIs) have been examined for their impact on the R_t.[11] South Carolina put various policies into place from March 16, 2020, through October 5, 2020, primarily in the form of executive orders.

The purpose of this study is to examine the change in the transmission potential of SARS-CoV-2 in South Carolina over time, especially before and after state or county-level public health policy interventions were put in place. We report the associations of R_t with these policies.

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Table 1. Policies enacted in South Carolina either by Executive Order or by local school districts, in the case of school re-opening

Label	Policy	Policy declaration	Start	End
C	Executive Order #9[20]	Schools closed	March 16, 2020	August through September 2020
	Executive Order #14[49]	Self-quarantine required for travelers from high-risk areas	March 27, 2020	May 1, 2020
N	Executive Order #18[21]	Closure of Other Nonessential Businesses (clarification)	April 3, 2020	May 22, 2020
R	Executive Order #37[22]	Re-opening of some nonessential businesses	May 22, 2020	Until end of State of Emergency
M	Executive Order #50[23]	Masks in government offices, restaurants, & large venues	August 2, 2020	Until superseded
S	Schools re-open	Schools reopened in Clarendon, Florence, Calhoun, and Jasper counties. These were the earliest re-opening dates in South Carolina.	August 17, 2020	N/A
L	Executive Order #63[24]	1. Individuals were required to wear face coverings and practice social distancing. 2. Restaurants were required to limit the seating at each table to no more than 8 customers and patron except for members from the same household. 3. The size of public gathering shall not exceed 50 percent of the location's occupancy limit or 250 persons.	October 2, 2020	Until end of State of Emergency

Note: The labels correspond to Figures 1, 2, and 3 where appropriate.

Methods

This study uses historic COVID-19 data from March 6, 2020, to January 10, 2021, from all 46 counties of South Carolina. South Carolina's Department of Health and Environmental Control divides the state into 4 regions: Upstate, Midlands, Pee Dee, and Low Country. A map of all counties in South Carolina by health region is provided in Supplementary Figure 1. Population by county is presented in Supplementary Figure 2. Cumulative case count and cumulative case count per 100,000 population, in April, August, October, and December 2020, are presented in Supplementary Figure 3.

Information about policies enacted in South Carolina was obtained from Executive Orders published online by the government of South Carolina. County level policies were obtained from county health departments. Information about school openings was obtained from school district websites, and in cases where schools had staggered openings (eg, middle schools starting before high schools), the earlier date was used. Detailed information on these policies including the date of the implementation and relaxation of public health interventions is presented in Table 1.

Data Acquisition

From the New York Times GitHub repository,[12] we downloaded the cumulative confirmed COVID-19 case count from March 6, 2020 to January 10, 2021. Data for the daily incidence were cleaned at the county level to eliminate any dates with negative incidence (Supplementary Materials, Appendix A). We selected a starting point of March 6, 2020, because the first case in South Carolina was reported on this date and a cutoff date of January 10, 2021 for all analyses. A 9-d backward shift was used to estimate the date of infection, accounting for a 6-d incubation period and a 3-d delay in testing. The error of this simple approach is considered tolerable if the delay to observation is not highly variable and if the mean delay is known.[8] This translated into the assumed date of infection from February 26, 2020, to January 1, 2021. Our choice of the cut-off point allowed us to complete the time series by the end of winter holiday season (Christmas to New Year). A sensitivity analysis was conducted using a lower boundary of 4 d and an upper boundary of 15 d based on incubation data reported by McAloon et al.[13] and CDC reports on testing delays.[14] We assessed the 2019 county-level population data for South Carolina from the US Census Bureau[15] and examined the power-law relationship between cumulative case count and population size through linear regression between the $\log_{10}$-transformed per capita cumulative case number and $\log_{10}$-transformed population size for each county.

Statistical Analysis

To calculate R_t, we used the instantaneous reproduction number method in the R package *EpiEstim* with the parametric option. This measure of the R_t was defined by Cori et al.[16] as the ratio between I_t, the number of incident cases at the time t, and the total infectiousness of all infected individuals at the time t. This R_t was used to describe the burden of COVID-19 at a state level and throughout certain counties.

The R_t is presented in 2 ways in this study. The first way is to take the average of the daily R_t estimates over a 7-d sliding window. The second way is to take the average of the daily R_t estimates over a nonoverlapping time window between 2 time points of policy changes (hereafter, known as policy change R_t in this study).

The policy change R_t was used to establish associations with policies. We calculated the percentage change for the policy change R_t for South Carolina (Supplemental Table 1), using the median policy change R_t estimate at each policy interval. For instance, the median policy change R_t estimate at each policy interval will be compared with the previous policy interval, as in $100\%\times(t_2-t_1)/t_1$. We used EpiEstim *sample from the posterior R distribution* function to obtain a sample of 1000 estimates of R_t for each t_1 and t_2 then estimate the credible intervals (2.5 and 97.5 percentile) of the percentage change. We also calculated the percentage change of the policy change R_t for Beaufort, Calhoun, Charleston, Colleton, Georgetown, Oconee, Orangeburg, Richland, and Williamsburg counties in South Carolina (Supplemental Table 2). These 9 counties were selected because they are the only counties with an active mask ordinance during the study period.

We characterized the power-law relationship between the county-level cumulative number of COVID-19 cases and population size, following C~N^g (C, cumulative case count; N, population size; g, exponent).[17] We performed linear regression

https://doi.org/10.1017/dmp.2022.212 Published online by Cambridge University Press

analysis between the $\log_{10}$-transformed per capita cumulative case count and the $\log_{10}$-transformed population size, ie, $\log_{10}(C/N) = m \log_{10}(N)$ where $m = g\text{-}1$.[17–19] We computed linear regression between the $\log_{10}$-transformed per capita cumulative case count and the $\log_{10}$-transformed population size, at 4 different dates: June 30, August 31, October 31, and December 31.

When per capita cumulative case count is proportional to population size, then there was no heterogeneity of per capita cumulative case count across geographic units (counties) of different population sizes (ie, when $m = 0$ and thus $g = 1$). Geographical units with lower population sizes would have a higher per capita cumulative case count if $m < 0$ (ie, $g < 1$) and those with lower population sizes would have a lower per capita cumulative case count if $m > 0$ (ie, $g > 1$).[18,19] See the Supplementary Materials Appendix B for details.

Statistical analysis was performed using R 4.0.3 (R Core Team, R Foundation for Statistical Computing, Vienna, Austria). Supplementary Figures 1, 2, and 3 were created using R 3.5.1 (R Core Team, R Foundation for Statistical Computing, Vienna, Austria).

Results

State Level – General

The daily new case count rose at the beginning of June 2020, and the peak of the first wave of cases arrived by mid-July. Case counts then started falling but remained higher than the beginning of the pandemic. By late September, case count rose again, and continued to rise through the end of the study period. Several days were reported with 0 cases, as data was not reported on federal holidays (Thanksgiving, Christmas Day, and New Year's Day). Figure 1 displays daily incident case count, 7-d sliding window R_t, and the policy change R_t, all right-adjusted for 9 d at the state level. The 7-d sliding window R_t throughout the state fluctuated between 2 and 3 in early March, and decreased to <1 during parts of April and May 2020. Over the summer, the R_t rose and continued to fluctuate between 0.7 and 1.4 throughout the state. At the end of the study period, the R_t was still above 1.0, indicating continued spread of the virus.

Policy Impacts – State Level

R_t fluctuated with policy changes at the state level. The R_t presented in this section refers to the policy change R_t. (Figure 1: lower panel, Supplementary Table 1). Before the introduction of any policies, the R_t was 1.991 (95% credible interval [CrI], 1.787, 2.21). The first policy introduced was the closure of schools on March 16.[20] Between the closure of schools and the closure of nonessential businesses, the R_t was 1.285 (95% CrI, 1.24, 1.33), a decrease of 35.59% (95% CrI, 27.9%, 42.7%).

The closure of nonessential businesses was ordered on April 3,[21] indicated by the label "N" in Figure 1. R_t dropped to 1.028 (95% CrI, 1.01, 1.05), a decrease of 20.01% (95% CrI, 18.8%, 21.1%), although the policy window was short. Some nonessential businesses were allowed to begin re-opening on May 22, following the issue of Executive Order 37.[22] The R_t associated with this timeframe was 1.05 (95% CrI, 1.04, 1.06), a statistically insignificant increase of 2.07% (95% CrI, −0.217 %, 4.2%).

The next Executive Order we examined was passed on August 2, 2020, mandating masks in government building, restaurants, and large venues.[23] This was associated with the first occurrence of R_t dropping below 1.0 in our policy examination. During this timeframe, the R_t was 0.889 (95% CrI, 0.873, 0.905), a decrease of 15.3% (95% CrI, 13.6%, 16.8%).

Our proxy date for school openings was August 17, 2020. This was based on the earliest reported dates for school openings. The R_t rose following this date to 0.998 (95% CrI, 0.989, 1.01), an increase of 12.3% (95% CrI, 10.1%, 14.4%). The final policy in this analysis was enacted on October 2, allowing restaurants to reopen for indoor dining and lifting capacity limits.[24] This was followed by an increase in R_t to 1.098 (95% CrI, 1.09, 1.1), increasing by 9.994% (95% CrI, 9.47%, 10.5%). This indicated sustained transmission of COVID-19 in South Carolina.

Sensitivity analysis was conducted to examine the effect of the assumption of the time lag. A 15-d time lag (Supplementary Figure 4) and a 4-d time lag (Supplementary Figure 5) were applied to the time series of the state-level case count data and no major differences between the main results and the lagged results were observed.

Mask Mandates – County Level

The wearing of masks has been advised for the general public since early April of 2020.[25] However, the requirement for face mask wearing was left up to each state, likely due to the federal polity of the United States and the political atmosphere in 2020.[26] For the purposes of this study, a "mask mandate" is any order given by authority for residents of a certain area to wear a mask or face covering while in specified locations. In South Carolina, the first Executive Order to mandate masks was issued on August 3, 2020.[20] This Order only mandated masks in government buildings, restaurants, and large venues.

Several counties (Beaufort, Charleston, Georgetown, Orangeburg, Richland, and Williamsburg) issued their own mask ordinances before the state. Three counties (Calhoun, Colleton, and Oconee) issued a mask ordinance after the statewide order was passed. We showed the policy change R_t for these counties in Figure 2 and Figure 3. These 9 counties were the only counties with an active mask ordinance during the study period (Supplementary Table 2).

The first counties we examined were those that passed the county-level mask ordinance before the state mandate. Beaufort County passed its ordinance on July 3, 2020.[27] The R_t decreased from 1.2283 (95% CrI, 1.17, 1.29) to 0.9856 (95% CrI, 0.946, 1.027), a decrease of 19.76% (95% CrI, 16.7%, 22.9%). Charleston County passed its face mask ordinance on July 1, 2020.[28] After the county ordinance passed, the R_t dropped from 1.2526 (95% CrI, 1.22, 1.28) to 0.8774 (95% CrI, 0.855, 0.90), decreasing by 29.95% (95% CrI, 29.9%, 30.0%). Georgetown County's mask ordinance passed on July 3, 2020.[29] The R_t decreased to 0.9596 (95% CrI, 0.891, 1.032) from 1.1980 (95% CrI, 1.11, 1.29), a decrease of 19.89% (95% CrI, 12.8%, 26.5%). Orangeburg County passed its face mask ordinance on July 3, 2020,[30] and its R_t estimates decreased from 1.2002 (95% CrI, 1.13, 1.28) to 0.9585 (95% CrI, 0.908, 1.011) with a decrease of 20.16% (95% CrI, 13.5%, 26.7%). Richland County passed its face mask ordinance on July 6, 2020,[31] and its R_t estimates decreased from 1.1729 (95% CrI, 1.14, 1.21) to 0.9529 (95% CrI, 0.922, 0.984), a decrease of 18.76% (95% CrI, 18.7%, 18.8%). Finally, Williamsburg County's R_t decreased after the introduction of their mask ordinance on July 9, 2020,[32] from 1.1342 (95% CrI, 1.02, 1.26) to 1.0013 (95% CrI, 0.912, 1.069), a decrease of 11.75% (95% CrI, 1.1%, 21.4%).

Calhoun, Colleton, and Oconee counties had their county level mask ordinances passed after the August 3 state mask mandate

https://doi.org/10.1017/dmp.2022.212 Published online by Cambridge University Press

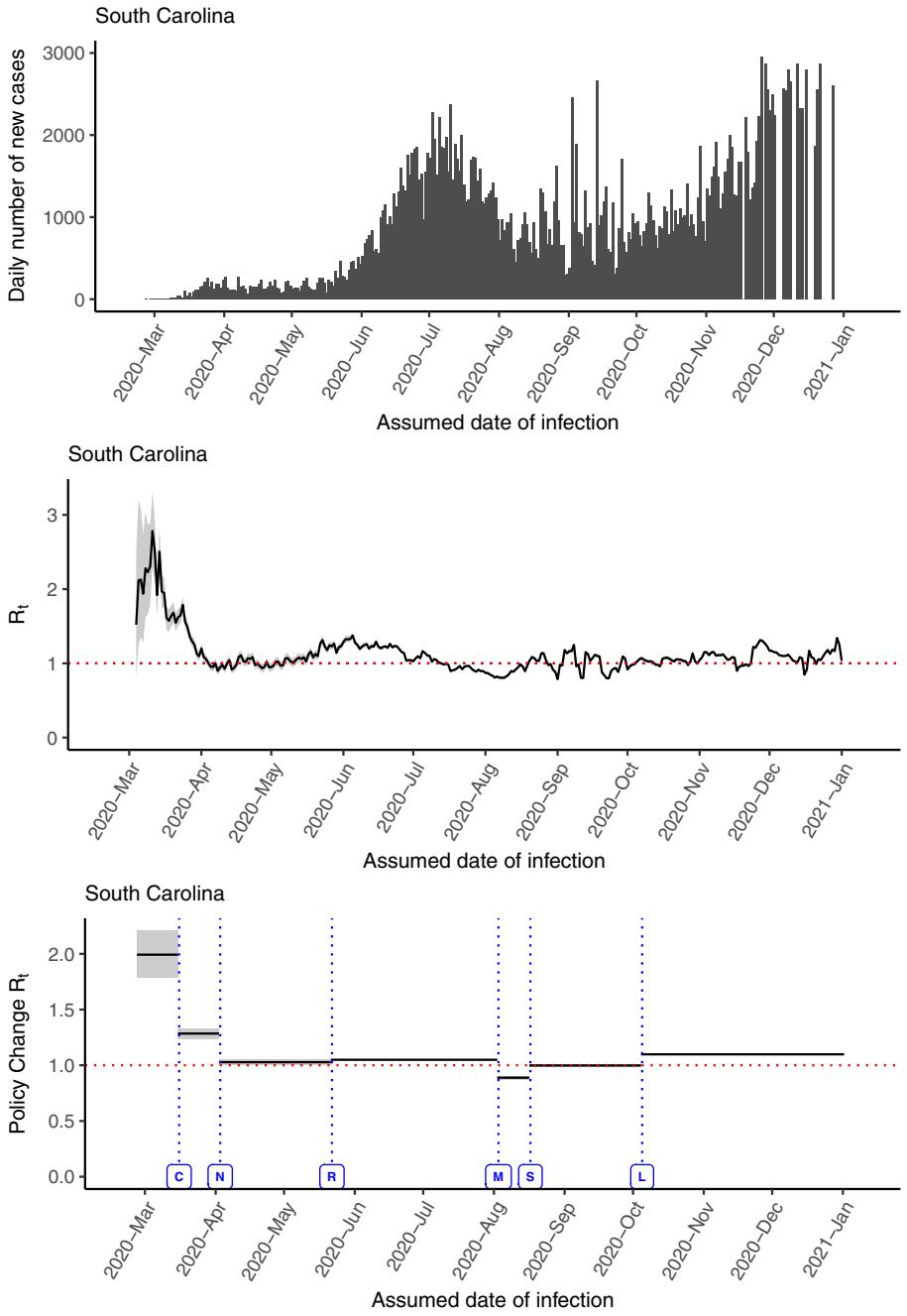

Figure 1. Daily number of new cases, 7-d sliding window R_t, and Policy Change R_t for the state of South Carolina. All case count data have been shifted backward by 9 d to approximate the date of infection. Data were not reported on holidays (Thanksgiving, Christmas, and New Year's Day). Policy Change R_t labels: C: Closure of schools (March 16, 2020), N: Closure of nonessential businesses (April 3, 2020), R: Re-opening of nonessential businesses (May 22, 2020), M: State level mask mandate (August 2, 2020), S: Re-opening of schools using earliest reported date (August 17, 2020), L: Capacity limits on public gathering changed to 250 (October 2, 2020).

(Figure 3, top panel). Among them, Oconee County passed a county-level mask ordinances on August 18 before the school re-opening.[33] After the county-level ordinance passed, the R_t further decreased from 1.0591 (95% CrI, 0.901, 1.235) to 1.0259 (95% CrI, 0.89, 1.17), a decrease of 3.16% (95% CrI, 1.21%, 4.91%). However, Calhoun County and Colleton County passed their county-level face mask ordinances much later than the state level mask mandate and months after the schools reopened in the Fall. Colleton County passed the county-level face mask ordinances on November 10, 2020,[34] and the R_t increased by 9.0% (95% CrI: −0.719%, 19.01%) from 1.0353 (95% CrI: 0.943, 1.133) to 1.1287 (95% CrI: 1.05, 1.21), but the increase was statistically insignificant. Last, Calhoun County passed their county-level face mask ordinances on December 18, 2020,[35] and the R_t increased from 1.0737 (95% CrI: 0.965, 1.19) to 1.101 (95% CrI: 0.941, 1.278), but the increase of 2.82% (95% CrI, −12.8%, 22.0%) was statistically insignificant.

School Openings

School openings were examined in both Figures 1, 2, and 3. In Figure 1, school re-opening is indicated by label "S", where

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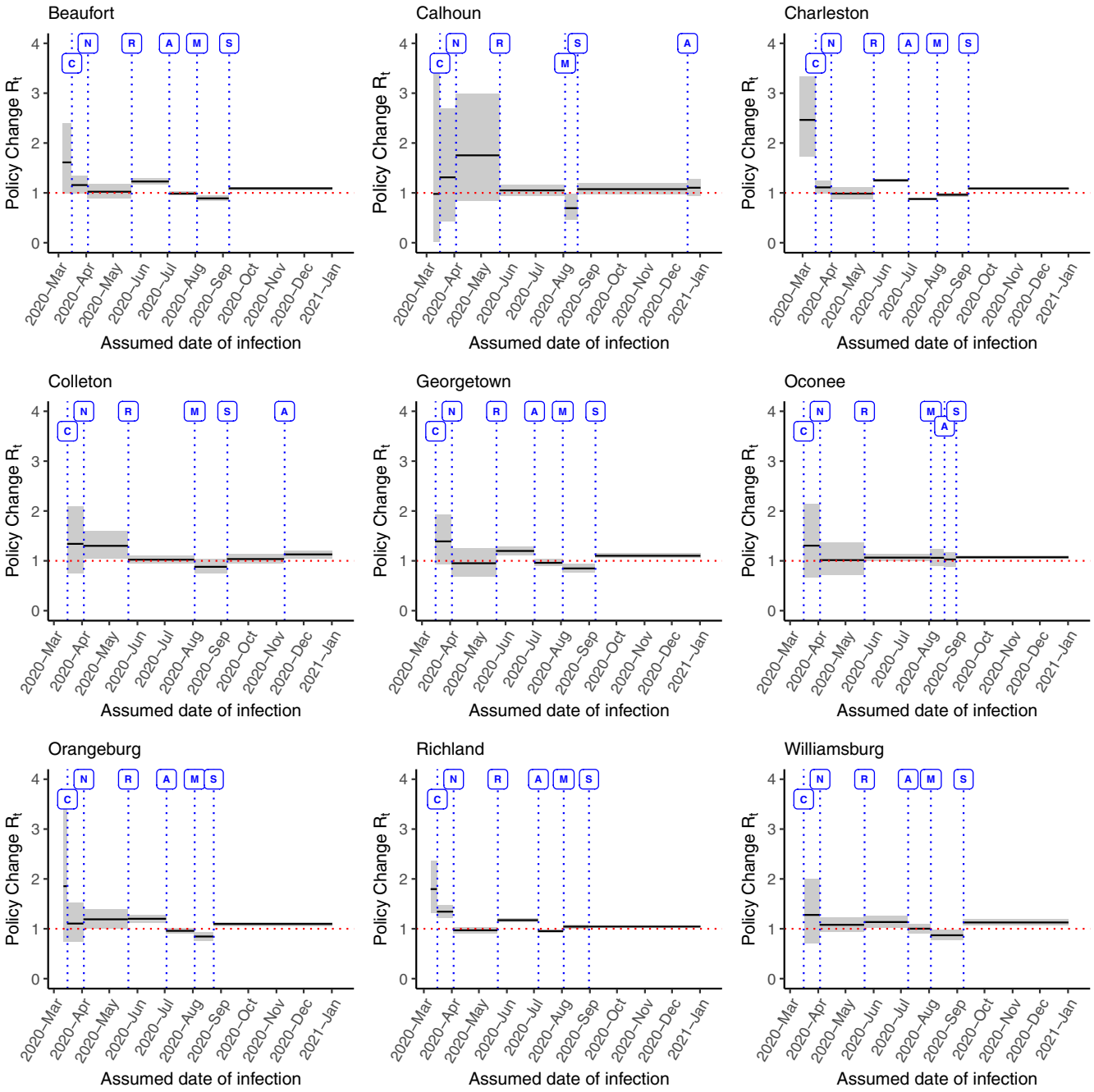

Figure 2. Policy change R_t in counties with mask mandates in South Carolina. Labels – C: Closure of schools (March 16, 2020), N: Closure of nonessential businesses (April 3, 2020), R: Re-opening of nonessential businesses (May 22, 2020), A: County level mask ordinance (varied, please refer to Figure 3), M: State mask mandate (August 2, 2020), S: Start of school, based on the earliest date in the county (varied, please refer to Figure 3). County locations can be found in Supplementary Figure 1.

we used a proxy date of August 17, the earliest reported school opening date across the state. It is important to note that these school openings are based on K through 12 schools' starting dates and not college starting dates. Some schools reopened in a staggered way by grade. Following school openings, the R_t in South Carolina rose by 12.3% (95% CrI, 10.1%, 14.4%) from 0.889 (95% CrI, 0.873, 0.91) to 0.998 (95% CrI, 0.989, 1.01).

At the county level (Figures 2 and 3), R_t increased when schools were re-opened in most counties. In Beaufort County, the increase was 22.57% (95% CrI, 16.7%, 27.7%) from 0.8903 (95% CrI, 0.839, 0.944) to 1.0916 (95% CrI, 1.06, 1.12). Calhoun County's R_t increased from 0.6857 (95% CrI, 0.461, 0.974) to 1.0737 (95% CrI, 0.965, 1.19), an increase of 56.29% (95% CrI, 9.66%, 127.21%). In Charleston County, the R_t rose by 13.03% (95% CrI, 10.9%, 15.1%) from 0.9621 (95% CrI, 0.927, 0.998) to 1.0878 (95% CrI, 1.07, 1.11). The Colleton County R_t increased by 17.77% (95% CrI, −1.33%, 38.12%) from 0.8782 (95% CrI, 0.74, 1.03) to 1.0353 (95% CrI, 0.943, 1.133), but the increase was statistically insignificant. The R_t in Georgetown County rose from 0.8468 (95% CrI, 0.762, 0.937) to 1.1016 (95% CrI, 1.06, 1.14), increasing by 29.9% (95% CrI, 15.6%, 45.1%).

Oconee County had a statistically insignificant increase of 4.25% (95% CrI, −9.85%, 20.29%) in R_t from 1.0259 (95% CrI, 0.89, 1.17) to 1.0710 (95% CrI, 1.04, 1.11). Orangeburg County

https://doi.org/10.1017/dmp.2022.212 Published online by Cambridge University Press

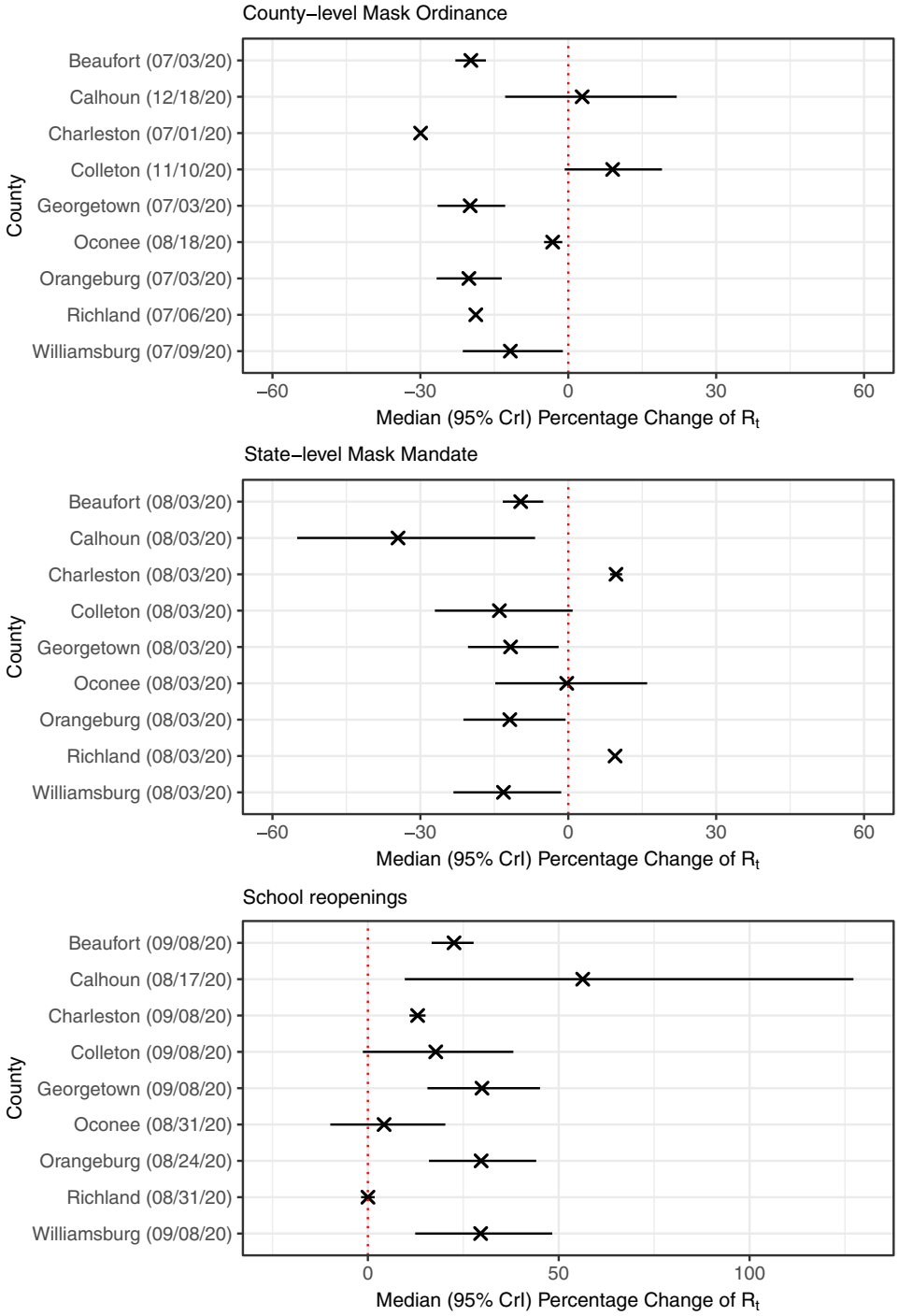

Figure 3. Median percentage change (95% CrI) of policy change R_t estimates for 9 selected counties organized by nonpharmaceutical interventions (county-level mask ordinance, state-level mask mandate, and school re-openings). The vertical line at zero percentage change on the x-axis indicated an increase in R_t (positive percentage changes) to its right and a decrease in R_t (negative percentage changes) to its left.

had an increase in R_t from 0.8447 (95% CrI, 0.763, 0.932) to 1.0972 (95% CrI, 1.06, 1.14), an increase of 29.67% (95% CrI, 16.0%, 44.1%). In Richland County, the R_t increased slightly from 1.0434 (95% CrI, 1.01, 1.08) to 1.0439 (95% CrI, 1.03, 1.06), but the increase of 0.016% (95% CrI, −1.78%, 1.79%) was statistically insignificant. Williamsburg County's R_t increased to 1.1264 (95% CrI: 1.07, 1.19) from 0.8692 (95% CrI: 0.767, 0.98), an increase of 29.54% (95% CrI: 12.4%, 48.3%).

Power-Law Relationship Between Cumulative Case Number and Population Size

Figure 4 presents the linear regression models between the $\log_{10}$-transformed per capita cumulative case number and the $\log_{10}$-transformed population size for a total of 46 counties in South Carolina at 4 different dates of report, June 30, August 31, October 31, and December 31, 2020, respectively. Each regression line represents a specific assessed date (date of report); and the

https://doi.org/10.1017/dmp.2022.212 Published online by Cambridge University Press

Table 2. The slope (and 95% confidence intervals) of the regression line between $\log_{10}$-transformed per capita cumulative count and $\log_{10}$-transformed population size by county in South Carolina, USA, on June 30, August 31, October 31, and December 31, 2020 (date of report)

Date of case report	Slope (m) and 95% CI	*P*-value
June 30, 2020	-2.0236 (−2.8233, −1.2239)	$P < 0.0001$
August 31, 2020	−1.2164 (−1.6712, −0.7615)	$P < 0.0001$
October 31, 2020	−1.0220 (−1.4088, −0.6352)	$P < 0.0001$
December 31, 2020	−1.0577 (−1.4456, −0.6697)	$P < 0.0001$

slopes, m, of 4 regression lines were calculated and documented in Table 2. Slopes of 4 regression lines were negative ($m < 0$) and statistically significant ($m = -2.0236, -1.2164, -1.0220, -1.0577$; $P < 0.0001$, respectively). A negative slope suggests that counties with lower population sizes (ie, rural counties) would have a higher per capita cumulative case count. This result suggests the existence of potential health disparities between urban and rural counties.

Discussion

This study examined the associations between SARS-CoV-2 R_t and public health policy changes throughout South Carolina from February 2020 to January 2021. We specifically examined the impacts of mask mandates at a county level and the resumption of in-person school activities (Figures 2 and 3). We found that mask mandates were frequently associated with a decrease in R_t while school re-openings were frequently associated with an increase in R_t.

We found that in Beaufort, Charleston, Georgetown, Oconee, Orangeburg, Richland, and Williamsburg counties, where a mask mandate was introduced at the county level before the state level mandate, a decrease in R_t was associated with the introduction of the policy. This suggested that county-level facemask mandate did have its utility in dampening SARS-CoV-2 transmission. In Oconee County, the state-level facemask mandate happened before the county-level facemask mandate. The county-level mandate apparently led to a slight further decrease in R_t.

In 2 counties, Calhoun and Colleton, the introduction of a county-level mask mandate happened late in 2020, after the introduction of the state-level mask mandate and the re-opening of schools. In both cases, R_t dropped below 1 after the state mask mandate but increased to levels above 1 after schools reopened. Our results suggest that the county-level mandates were introduced too late to have a significant impact on R_t. The increased R_t after the county-level mask mandate should be interpreted as a continuation of an increase in R_t despite the county-level mask mandate. Additionally, by late 2020, adherence fatigue[36] might also impact how well facemask mandates were followed.

We also examined school re-openings in counties that had county level mask mandates in place (Figures 2 and 3). In these counties, the R_t fell when the county mask mandate was put in place. In most places the R_t lowered again when the state mandate was put into place, although in Charleston and Richland counties the R_t did rise after the state mandate. This may be due to adherence fatigue[37] in the summer months. Richland county includes Columbia, the state capital. Columbia is highly populated and is the site of the University of South Carolina main campus. Case counts here might be impacted by the university opening (such as student parties that turned out to be super-spreading events).[38] Charleston is a tourist destination, so potentially an increase in late summer tourism could have driven the R_t higher despite the statewide mask mandate, especially as the mandate only required masks in government buildings, restaurants, or large venues. Similar observations can be said of Beaufort County, where the tourist destination Hilton Head Island is located. While the county's and state's mask mandates were associated with R_t decreasing to below 1 in Beaufort, R_t increased after school re-opening in September.

Other literature supports the notion that mask mandates may slow the transmission of SARS-CoV-2.[39] Hua et al. found that a mask mandate was associated with a decrease in R_t by 27% in North Dakota, by 16% in Montana and by 13% in Wyoming.[40] Politis et al. found facemask mandate was associated with a decrease in R_t by 11% and 6%, respectively, in Arkansas and Kentucky.[10] Thus, our findings in South Carolina are consistent with findings in other states that a mask mandate was associated with slowing epidemic growth.

The role of school re-openings in COVID-19 transmission has been examined as well.[37,41–44] A high school in Israel reported a COVID-19 outbreak shortly after a school reopened in May 2020.[42] Another study modeled school re-opening, and found that reduction in capacity and mask wearing could reduce community transmission, whereas higher capacity and nonadherence to mask wearing could drive COVID-19 spread in the school's community.[44] According to our analyses (Figures 2 and 3), the percentage changes of policy change R_t estimates increased in 8 of 9 selected counties, except Richland County. This observation echoes existing studies that school re-openings have the potential to spread COVID-19 in the local communities.[37,42–44] Similar to our findings, Hua et al. found an increase in R_t in Idaho (13%), Montana (21%), South Dakota (12%), and Wyoming (20%) after school reopened on September 7, 2020; however, the same study found a decrease in R_t by 8% in North Dakota after school re-opening on the same date.[40] Politis et al. found that after school reopened, R_t increased by 12% and 9% in Arkansas and Kentucky, respectively.[10] Thus, our findings in South Carolina are consistent with findings in other states in general, that school re-opening in August and September 2020 was associated with increased SARS-CoV-2 transmission as evidenced in an increase in R_t.

In addition, rural counties in South Carolina were found to have a higher per capita cumulative case count at 4 different assessed dates in 2020. This result suggests that rural counties bore a higher disease burden than urban counties. Future research may investigate the cause and related factors of such health disparities.

The focus of this study was on public health and social policy involving mandates of NPIs. The first COVID-19 vaccine in South Carolina was administered on December 15, 2020.[45] Our study period ended in early 2021 before the vaccination campaign could make an impact to slow SARS-CoV-2 transmission in South Carolina. Future research may study whether certain highly transmissible variants of concern may trigger COVID-19 resurgence.[46] While this is out of scope for this study, further research into the effect of policy mandates that target special populations such as residents of long-term care facilities and their caretakers may be conducted.[47]

Limitations

There are several limitations in this study. First, this analysis was based on aggregate data reported by the surveillance system of

https://doi.org/10.1017/dmp.2022.212 Published online by Cambridge University Press

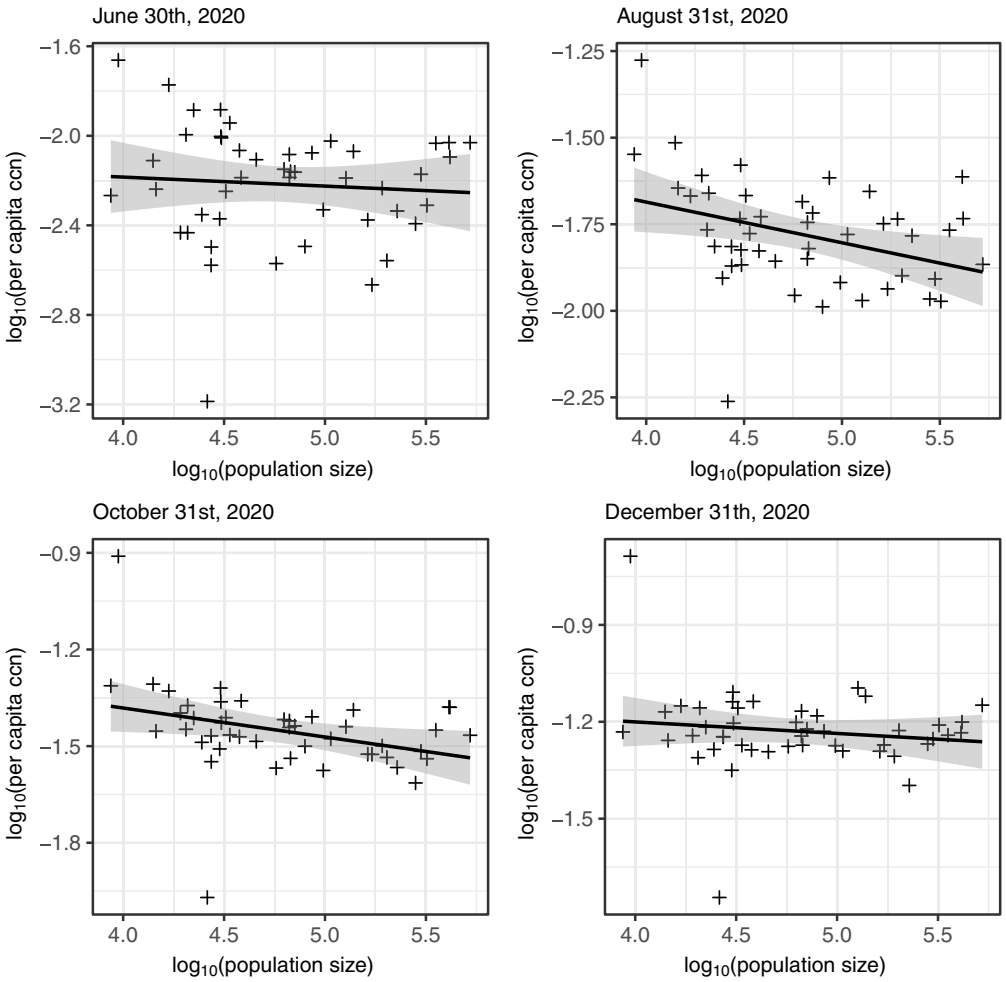

Figure 4. Linear regression between $\log_{10}$-transformed per capita cumulative case number (ccn) and $\log_{10}$-transformed population size by county for South Carolina on June 30, August 31, October 31, and December 31, 2020. Each plus sign represents a county in South Carolina.

COVID-19 in South Carolina. The data were arranged by date of report. Even though we shifted the date backward by 9 d to approximate the date of infection, this remained an estimation. Second, date of report is affected by holidays, on which days cases were not reported. Third, the effects of viral variants on transmission potential[46] cannot be shown in this study. The first 2 cases of the Beta (B.1.351) variant in the United States were detected in South Carolina after the study period ended,[48] so this may not be a severe limitation. Fourth, while re-opening of schools was staggered by grade in South Carolina, we lumped the re-openings together as we chose the first date of the re-opening as the date of policy change. However, for the county-level policy change analysis, we had specific school re-opening dates for all 9 selected counties (Figures 2 and 3). And finally, we do not examine the impact of vaccinations on the transmission potential in South Carolina; however, our study period ended by January 10, 2021 (date of report), by which point there were minimal numbers of people fully vaccinated.

Although we examined the impact of policy mandates, we did not examine the extent to which these policies were adhered on the ground. Behavioral variation in some places might impact the effectiveness of policies. However, as we attempted to examine the real-world effects of interventions on COVID-19 transmission potential, this would not be a serious limitation to the study.

Conclusions

The pandemic affected South Carolina starting with the first cases confirmed in early March 2020, and data suggest ongoing transmission from late February 2020 through the end of the study period (the beginning of 2021). Our findings suggest that public health policies that encourage the adoption of NPIs, such as mask mandates, were found to be associated with a decrease in R_t. In contrast, policies that encouraged more social interaction and population movement, such as re-opening schools for in-person instruction, were typically followed by an increase in R_t. In general, mask mandates appeared to work better in counties that implemented it early on than those that implemented it after the incidence trajectory had risen to a high level. Our study provided a state and county-level analysis that could support evidence-based decision-making in the adoption of NPIs at the population level against COVID-19. Our findings could prove useful for shaping future outbreak responses.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/dmp.2022.212.

Acknowledgement. The authors thank Prof. Anne C. Spaulding for her review of an earlier draft of the manuscript and for her helpful suggestions.

Author contributions. M.R.D. and X.H. contributed equally and they are co-first authors. Conceptualization: M.R.D., X.H., I.C.H.F.; Data analysis: M.R.D., X.H.; Literature review: M.R.D., X.H., T.D.J., G.I.W.; Map creation: P.Y.L.; Writing the first draft of the manuscript: M.R.D.; Major revision of the manuscript: X.H., I.C.H.F.; Manuscript Editing: Z.D., S.D., S.W.R., G.C., I.C.H.F.; Mentoring student authors: I.C.H.F.

Funding statement. No external funding was provided.

Conflict of interest. No conflicts of interest are declared.

Ethical standards. The Georgia Southern University Institutional Review Board made a nonhuman subject determination for this project (H20364) under the G8 exemption category according to the Code of Federal Regulations Title 45 Part 46.

References

1. **Allam Z.** The first 50 days of COVID-19: a detailed chronological timeline and extensive review of literature documenting the pandemic. *Surveying The Covid-19 Pandemic and Its Implications*. Elsevier; 2020:1-7.
2. **Holshue ML, DeBolt C, Lindquist S, *et al.*** First case of 2019 novel coronavirus in the United States. *N Engl J Med.* 2020;382(10):929-936. doi: 10.1056/NEJMoa2001191
3. **US Census Bureau**. QuickFacts. South Carolina website. Published 2021. Accessed February 27, 2022. https://www.census.gov/quickfacts/SC
4. **South Carolina Office of the Governor**. Executive Order No. 2020-08. Website. Published 2020. Accessed April 10, 2021. https://governor.sc.gov/sites/default/files/Documents/Executive-Orders/2020-03-13%20FILED%20Executive%20Order%20No.%202020-08%20-%20State%20of%20Emergency%20Due%20to%20Coronavirus%20(COVID-19).pdf
5. **Vynnycky E, White RG.** *An Introduction to Infectious Disease Modelling*. Oxford University Press; 2010.
6. **Li Q, Guan X, Wu P, *et al.*** Early transmission dynamics in Wuhan, China, of novel coronavirus–infected pneumonia. *N Engl J Med.* 2020;382(13):1199-1207. doi: 10.1056/NEJMoa2001316
7. **Muniz-Rodriguez K, Fung IC-H, Ferdosi SR, *et al.*** Severe acute respiratory syndrome coronavirus 2 transmission potential, Iran, 2020. *Emerg Infect Dis.* 2020;26(8):1915-1917. doi: 10.3201/eid2608.200536
8. **Gostic KM, McGough L, Baskerville EB, *et al.*** Practical considerations for measuring the effective reproductive number, Rt. *PLoS Comput Biol.* 2020;16(12):e1008409. doi: 10.1371/journal.pcbi.1008409
9. **Fung IC-H, Hung YW, Ofori SK, *et al.*** SARS-CoV-2 transmission in Alberta, British Columbia, and Ontario, Canada, December 25, 2019 - December 1, 2020. *Disaster Med Public Health Prep.* 2021. doi: 10.1017/dmp.2021.78
10. **Politis MD, Hua X, Ogwara CA, *et al.*** Spatially refined time-varying reproduction numbers of SARS-CoV-2 in Arkansas and Kentucky and their relationship to population size and public health policy, March - November 2020. *Ann Epidemiol.* 2022;68:37-44. doi: 10.1016/j.annepidem.2021.12.012
11. **Li Y, Campbell H, Kulkarni D, *et al.*** The temporal association of introducing and lifting non-pharmaceutical interventions with the time-varying reproduction number (R) of SARS-CoV-2: a modelling study across 131 countries. *Lancet Infect Dis.* 2021;21(2):193-202.
12. **New York Times**. New York Times/covid-19 data. Website. Accessed January 11, 2021. https://github.com/nytimes/covid-19-data Published 2021.
13. **McAloon C, Collins Á, Hunt K, *et al.*** Incubation period of COVID-19: a rapid systematic review and meta-analysis of observational research. *BMJ Open.* 2020;10(8):e039652. doi: 10.1136/bmjopen-2020-039652
14. **Centers for Disease Control and Prevention**. COVID-19 Pandemic Planning Scenarios. Website. Published 2020. Accessed March 10, 2021. https://www.cdc.gov/coronavirus/2019-ncov/hcp/planning-scenarios.html
15. **US Census Bureau**. County Population Totals: 2010–2019. Website. Published 2021. Accessed February 27, 2022. https://www.census.gov/data/tables/time-series/demo/popest/2010s-counties-total.html
16. **Cori A, Ferguson NM, Fraser C, *et al.*** A new framework and software to estimate time-varying reproduction numbers during epidemics. *Am J Epidemiol.* 2013;178(9):1505-1512. doi: 10.1093/aje/kwt133
17. **Chowell G, Bettencourt LMA, Johnson N, *et al.*** The 1918-1919 influenza pandemic in England and Wales: spatial patterns in transmissibility and mortality impact. *Proc Biol Sci.* 2008;275(1634):501-509. doi: 10.1098/rspb.2007.1477
18. **Fung IC-H, Zhou X, Cheung C-N, *et al.*** Assessing early heterogeneity in doubling times of the COVID-19 epidemic across prefectures in mainland China, January–February, 2020. *Epidemiologia*. 2021;2(1):95-113. https://www.mdpi.com/2673-3986/2/1/9
19. **Ogwara CA, Mallhi AK, Hua X, *et al.*** Spatially refined time-varying reproduction numbers of COVID-19 by health district in Georgia, USA, March-December 2020. *Epidemiologia*. 2021;2(2):179-197. doi:https://doi.org/10.3390/epidemiologia2020014
20. **South Carolina Office of the Governor**. Executive Order No. 2020-09. Website. Published 2020. Accessed April 10, 2021. https://governor.sc.gov/sites/default/files/Documents/Executive-Orders/2020-03-15%20FILED%20Executive%20Order%20No.%202020-09%20-%20Closing%20Schools%20Cancelling%20Elections%20Other%20Provisions%20Due%20to%20COVID-19.pdf.
21. **South Carolina Office of the Governor**. Executive Order No. 2020-18. Website. Published 2020. Accessed April 10, 2021. https://governor.sc.gov/sites/default/files/Documents/Images/2021-04-07%20FILED%20Executive%20Order%20No.%202021-18%20-%20State%20of%20Emergency.pdf
22. **South Carolina Office of the Governor**. Executive Order No. 2020-37. Website. Published 2020. Accessed April 10, 2021. https://governor.sc.gov/sites/default/files/Documents/2020-05-21%20FILED%20Executive%20Order%20No.%202020-37%20-%20Additional%20Incremental%20Modification%20of%20Non-Essential%20Business%20Closures.pdf
23. **South Carolina Office of the Governor**. Executive Order No. 2020-50. Website. Published 2020. Accessed April 10, 2021. https://governor.sc.gov/sites/default/files/Documents/Executive-Orders/2020-08-02%20FILED%20Executive%20Order%20No.%202020-50%20-%20Initiating%20Additional%20Emergency%20Measures%20%26%20Consolidating%20Previous%20Orders.pdf
24. **South Carolina Office of the Governor**. Executive Order No. 2020-63. Website. Published 2020. Accessed April 10, 2021. https://governor.sc.gov/sites/default/files/Documents/Executive-Orders/2020-10-02%20FILED%20Executive%20Order%20No.%202020-63%20-%20Amending%20%26%20Consolidating%20Emergency%20Measures.pdf
25. **Dwyer C, Aubrey A.** CDC now recommends Americans consider wearing cloth face coverings in public. Website. Published 2020. Accessed August 25, 2022. https://www.npr.org/sections/coronavirus-live-updates/2020/04/03/826219824/president-trump-says-cdc-now-recommends-americans-wear-cloth-masks-in-public
26. **Balmford B, Annan JD, Hargreaves JC, *et al.*** Cross-country comparisons of Covid-19: policy, politics and the price of life. *Environ Resour Econ.* 2020;76(4):525-551. doi: 10.1007/s10640-020-00466-5
27. **Beaufort County**. Face masks to be required in unincorporated Beaufort County. Website. Published 2020. Accessed April 12, 2021. https://www.beaufortcountysc.gov/news/2020/07/face-masks-to-be-required-in-unincorporated-beaufort-county.html
28. **City of Charleston**. City of Charleston coronavirus updates. Website. Accessed April 12, 2021. https://www.charleston-sc.gov/2408/City-of-Charleston-Coronavirus-Updates
29. **City of Georgetown South Carolina**. Face mask ordinance. Website. Published 2020. Accessed April 12, 2021. https://georgetownsc.gov/face-mask-ordinance/
30. **City of Orangeburg South Carolina**. City face mask ordinance 6-30-20. Website. Published 2020. Accessed April 12, 2021. https://www.orangeburg.sc.us/sites/default/files/uploads/images/covid-19/2020-04_city_face_mask_ordinance_6-30-20.pdf
31. **Richland County South Carolina**. Richland County Council adopts emergency COVID-19 mask ordinance. Website. Published 2020. Accessed April 12, 2021. https://www.richlandcountysc.gov/Home/News/ArtMID/479/ArticleID/2054/Richland-County-Council-Adopts-Emergency-COVID-19-Mask-Ordinance.

32. **Laudenslager C.** Williamsburg County passes mask ordinance. Website. Published 2020. Accessed April 12, 2021.https://www.counton2.com/news/local-news/williamsburg-county-passes-mask-ordinance/.
33. **Oconee County South Carolina**. State of South Carolina County of Oconee Ordinance 2020-14(E). Website. Published 2020. Accessed April 12, 2021. https://oconeelibrary.org/wp-content/uploads/sites/7/2020/05/Ordinance-2020-14-E.pdf
34. **Colleton County South Carolina**. Emergency Ordinance No.20-O-11. Website. Published 2020. Accessed April 12, 2021. https://www.colletoncounty.org/Data/Sites/1/media/covid-19/20-o-11-mask-ordinance-november-10,-2020.pdf
35. **Harris B.** Calhoun County approves face mask ordinance. Website. Published 2020. Accessed August 25, 2022. https://thetandd.com/news/local/government-and-politics/calhoun-county-approves-face-mask-ordinance/article_80a5baf8-4e6f-5881-a4ca-761a8927d233.html
36. **Rahmandad H, Lim TY, Sterman J.** Behavioral dynamics of COVID-19: estimating underreporting, multiple waves, and adherence fatigue across 92 nations. *Syst Dyn Rev*. 2021;37(1):5-31. doi: 10.1002/sdr.1673
37. **Fantini MP, Reno C, Biserni GB, *et al.*** COVID-19 and the re-opening of schools: a policy maker's dilemma. *Ital J Pediatr*. 2020;46(1):79. doi: 10.1186/s13052-020-00844-1
38. **TMZ**. S.C. college bar pakced to the gills . . . not the Corona you want. Website. Published 2020. Accessed August 15, 2021. https://www.tmz.com/2020/09/04/college-students-pack-bar-south-carolina-covid/
39. **Cheng VC-C, Wong S-C, Chuang VW-M, *et al.*** The role of community-wide wearing of face mask for control of coronavirus disease 2019 (COVID-19) epidemic due to SARS-CoV-2. *J Infect*. 2020;81(1):107-114. doi:https://doi.org/10.1016/j.jinf.2020.04.024
40. **Hua X, Kehoe ARD, Tome J, *et al.*** Late surges in COVID-19 cases and varying transmission potential partially due to public health policy changes in 5 Western states, March 10, 2020-January 10, 2021. *medRxiv*. 2021. doi:https://doi.org/10.1101/2021.07.04.21259992
41. **Kuehn BM.** COVID-19 rates increased where in-person college classes were held. *JAMA*. 2021;325(8):714. doi: 10.1001/jama.2021.0621
42. **Stein-Zamir C, Abramson N, Shoob H, *et al.*** A large COVID-19 outbreak in a high school 10 days after schools' reopening, Israel, May 2020. *Euro Surveill*. 2020;25(29):2001352. doi: 10.2807/1560-7917.ES.2020.25.29.2001352
43. **Leeb RT, Price S, Sliwa S, *et al.*** COVID-19 trends among school-aged children - United States, March 1-September 19, 2020. *MMWR Morb Mortal Wkly Rep*. 2020;69(39):1410-1415. doi: 10.15585/mmwr.mm6939e2
44. **España G, Cavany S, Oidtman R, *et al.*** Impacts of K-12 school reopening on the COVID-19 epidemic in Indiana, USA. *Epidemics*. 2021;37:100487. doi: 10.1016/j.epidem.2021.100487
45. **Wilks AG.** First South Carolina coronavirus vaccines administered to health care workers. Website. Published 2020. Accessed May 13, 2022. https://www.postandcourier.com/health/covid19/first-south-carolina-coronavirus-vaccines-administered-to-health-care-workers/article_efc5e38a-3bf9-11eb-a85d-9fbfd1f767eb.html
46. **Darby AC, Hiscox JA.** Covid-19: variants and vaccination. *BMJ*. 2021;372:n771. doi: 10.1136/bmj.n771
47. **Lai CC, Wang J-H, Ko W-C, *et al.*** COVID-19 in long-term care facilities: an upcoming threat that cannot be ignored. *J Microbiol Immunol Infect*. 2020;53(3):444-446. doi: 10.1016/j.jmii.2020.04.008
48. **Department of Health and Environmental Control**. South Carolina Public Health Officials detect nation's first known cases of the COVID-19 variant originally detected in South Africa. Website. Published 2021. Accessed April 2, 2021. https://scdhec.gov/news-releases/south-carolina-public-health-officials-detect-nations-first-known-cases-covid-19
49. **South Carolina Office of the Governor**. Executive Order No.2020-14. Website. Published 2020. Accessed April 10, 2021. https://governor.sc.gov/sites/default/files/Documents/Executive-Orders/2020-03-27%20FILED%20Executive%20Order%20No.%202020-14%20-%20Self-Quarantine%20for%20Individuals%20from%20High-Risk%20Areas.pdf

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