

Original Research

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Geographical Variation in COVID-19 Transmission Potential and Case Burden, West Virginia, 2020-2023

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Abstract

Objective: Substate-level analysis reveals geographical variation in COVID-19 epidemiology and facilitates improvement of prevention efforts with greater granularity.

Methods: We analyzed daily confirmed COVID-19 case count in West Virginia and its 9 regions (March 19, 2020–March 9, 2023). Nonparametric bootstrapping and a Poisson-distributed multiplier of 4 were applied to account for irregular and under-reporting. We used the R package EpiEstim to estimate the time-varying reproduction number R_t with 7-day-sliding-windows (2020–2023) and non-overlapping-time-windows between 5 policy changes (2020 only). Poisson regression was used to estimate the incidence rate ratio (IRR) between each region and West Virginia (2020, 2021, and 2022).

Results: Statewide R_t fluctuated over the study period, with the highest in March 2020 (close to 2) and the lowest R_t (<1) seen in June 2020. The Stay-at-home Order, Face Mask Mandate, and Virtual Learning Resumes saw 38.7% (95% credible interval [CrI]: 21.9%–57.5%), 10.6% (95% CrI, 3.2%–18.9%), and 9.4% (95% CrI, 3.2%–15.4%) corresponding decreases in R_t statewide. All regions experienced incidence rates different from the state. The IRRs ranged from 0.32 (95% CI, 0.32–0.33) (Northern region) to 1.90 (95% CI, 1.87–1.94) (Wood-Jackson region) in 2020.

Conclusions: Policies reducing human contacts, e.g., Stay-at-home Order and Virtual Learning Resumes, effectively reduced transmission statewide.

The SARS-CoV-2 virus has significantly impacted global populations. As the COVID-19 outbreak evolved into a pandemic by March 2020, the world, specifically the US, grappled with how to prevent this disease from spreading worldwide.¹ Since then, a massive surge of research and evaluation has been done to understand how the pandemic could have been handled better.^{2,3} Evaluation is crucial for improving public health across the globe. Providing evidence on factors that contributed to the spread and control of the pandemic can inform decision-makers of more evidence-based decisions in the future.

Time-varying reproduction number (R_t) is a version of the reproduction number metric that epidemiologists use to evaluate the transmission potential of infectious diseases in the presence of interventions. The reproduction number is the average number of secondary infections generated by 1 infectious person. R_t represents the reproduction number at a given time (t) in the presence of population immunity, behavioral changes, or public health interventions. The R_t value provides insight into how pathogens spread throughout a population during an outbreak.⁴ Specifically, R_t can be used to assess how effective a public health intervention is in controlling the spread of an infectious disease. Using the renewal equation and the generation time of the disease (proxied by serial interval), the R_t value can be estimated as it changes over time.⁴

West Virginia is located in the southeastern United States, in the heart of the Appalachian region. Although this region is known for its coal mining and other industrial projects, it is also geographically close to Washington D.C., Pittsburgh, PA, and Cleveland, OH. The capital of West Virginia, Charleston, hosts a sizeable metropolitan population that acts as an urban hub for various businesses, residents, and government buildings. The diversity found across the state,

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from rural to urban areas, makes West Virginia a cultural hub where differing views on how the pandemic should be handled intersect.

The purpose of this study is threefold. Firstly, we estimated the transmission potential of COVID-19 as the 7-day sliding window R_t from March 10, 2020–February 28, 2023. Secondly, we evaluated the impact of 5 policy changes in 2020 on R_t values in West Virginia and its 9 regions. Thirdly, we compared the case burden of each region in 2020, 2021, and 2022 by estimating the incidence rate ratio (IRR) through Poisson regression using the statewide case rate as the reference group.

Methods

Aggregated daily cumulative count data for West Virginia and its counties were downloaded from the COVID-19 Data Repository by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University.⁵ The time series covered the period from January 22, 2020–March 9, 2023, by the date of report. CSSE stopped retrieving case count data on March 10, 2023. In this study, the incident case count data were shifted backward by 9 days to approximate the date of infection before R_t estimation (see below),

with the time series ranging from January 13, 2020–February 28, 2023. The first reported case in West Virginia was recorded on March 19, 2020, with an estimated date of infection of March 10, 2020. We estimated the 7-day sliding window R_t from March 10, 2020–February 28, 2023. For the policy change R_t with non-overlapping time windows, we limited our analysis to the year 2020 (the time series of March 10, 2020, to December 31, 2020, by the estimated date of infection). We chose to limit policy change R_t analysis to 2020 because this method did not capture the gradual change in population immunity or the vaccine campaign rollout. The official vaccine rollout in West Virginia began on December 14, 2020.⁶

Unit of Analysis (Regions in West Virginia)

For our analysis, we divided the state of West Virginia into 9 distinct regions: Metro-Charleston, Clarksburg, Eastern, Western, Northern, Southern, Martinsburg, Morgantown, Wood-Jackson (Figure 1). We used the U.S. Census Bureau-defined Metropolitan Statistical Areas as a starting point for grouping counties into regions.⁷ Factors considered included county populations, West Virginia's major highways, and the potential to commute to highly

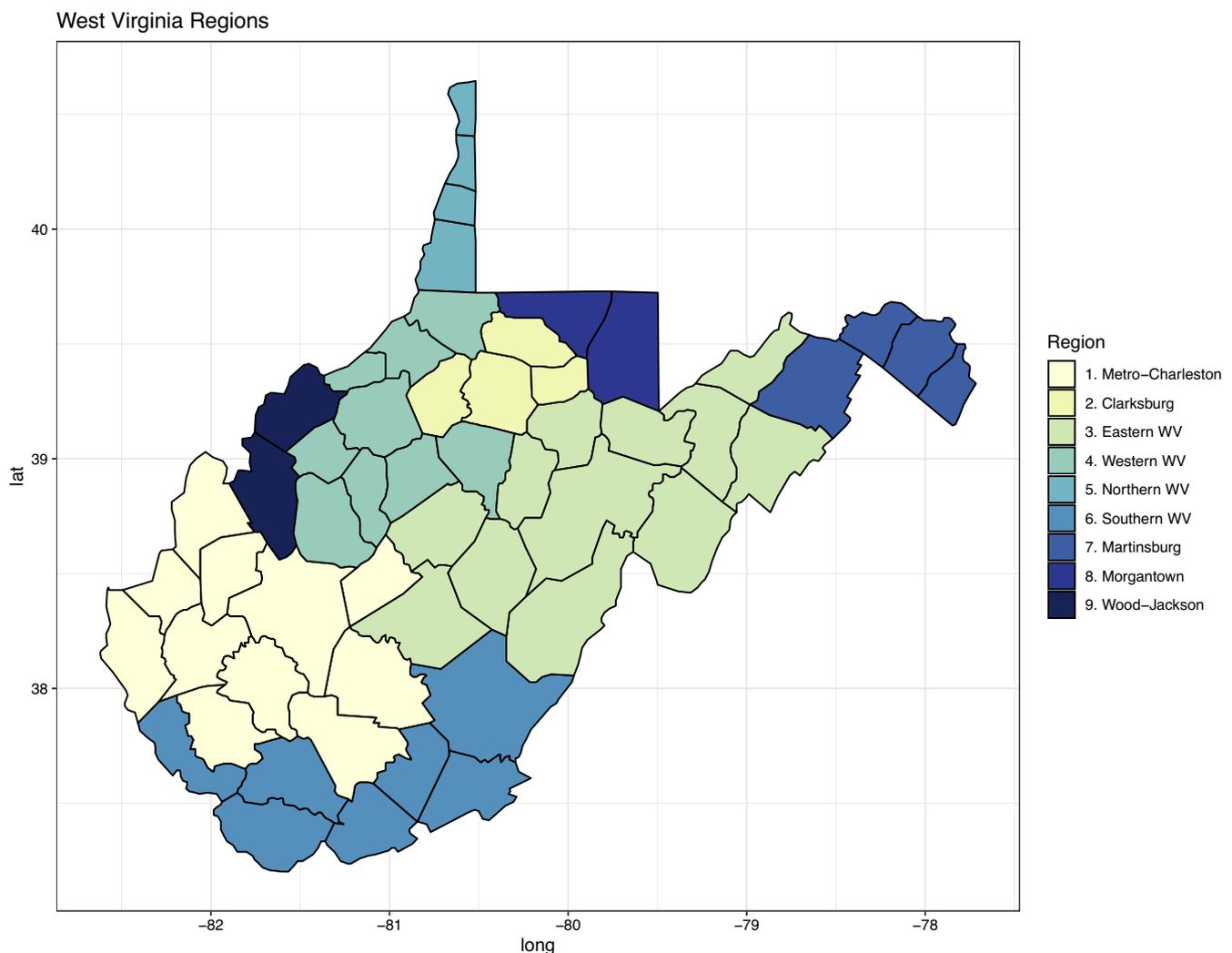


Figure 1. A map of West Virginia. Counties are grouped into 9 regions for analysis in this study. These regions are: (A) Metro-Charleston, (B) Clarksburg, (C) Eastern, (D) Western, (E) Northern, (F) Southern, (G) Martinsburg, (H) Morgantown, and (I) Wood-Jackson.

populated US cities. After rounds of deliberation between AAB, XH, JS, and ICHF, the team settled on the current grouping of counties into 9 regions. It is important to note that the 2 counties of Wood and Jackson were grouped into a stand-alone Wood-Jackson region because of the 3 populated towns in Wood County and the populations that live there.

R_t Estimation

The time-varying reproduction number, R_t , served as an indicator of the transmission potential of the virus at a given time t . A R_t value >1 means the epidemic is growing, while a R_t value <1 means the epidemic is declining. To approximate the time of infection and adjust for the mean incubation period of 6 days and the median lag from testing to report of 3 days, the time series of incidence cases was shifted backward by 9 days.⁸ During the data cleaning, negative case counts were replaced with a 3-day average from before and after the negative case count date. Nonparametric bootstrapping of the incident case count data with a rolling 15-day window (± 7 days) was performed to account for irregular reporting in the data. A Poisson-distributed multiplier (mean = 4) was applied to estimate infection count accounting for underreporting of asymptomatic and mildly symptomatic infections.⁹

7-Day-Sliding-Window R_t

To give an overview of how transmission potential changes over time, we estimated R_t from the estimated daily incident infection count by the estimated date of infection, March 10, 2020–February 28, 2023, using a 7-day sliding window. EpiEstim takes an average of the daily R_t estimates over a rolling 7-day period and therefore smooths the R_t curve.⁴ R_t was estimated over time for the state and each of the 9 regions.

Policy Change R_t

To estimate the percentage difference in R_t from first policy change to fifth policy change (“Policy change R_t ”), the estimated daily incident infection counts from March 10, 2020–December 31, 2020 (estimated date of infection) were analyzed. Six non-overlapping time windows were defined by 5 important dates on which behavioral pattern changes were initiated among the West Virginia populations. These dates were taken from the Department of Health and Human Services and the Governor of West Virginia’s Executive Orders, as defined in Table 1. The dates in 2020 were chosen as follows. On March 24, an Executive order to Stay at Home was issued.¹⁰ On May 4, the campaign “West Virginia - The Comeback” was initiated. The indoor mask mandate was instated on July 7. Schools reopened on September 9. Moreover, virtual learning resumed on November 14. An R_t value with its 95% credible interval (CrI) was estimated for each non-overlapping time window. Percentage change (and 95% CrI) was then calculated between each successive policy change R_t value. The same procedure was repeated for the statewide data and each of the 9 regions.

Incidence Rate Ratio

To estimate the difference in case burden across different regions of the state, an IRR of observed case count was calculated for each region for each year of 2020, 2021, and 2022 (date of report), using the state as the reference. Poisson regression models, using person-days observed as the offset, were used to test the null hypothesis that

the incident case rate for the state was equal to the incident case rate for each region. The number of days observed was 345, 365, and 365 in 2020, 2021, and 2022 respectively. 2020 was a leap year (366 days), and the time series began on January 22, 2020 (date of report), ending on December 31, 2022. The IRR analysis analyzed the incident case count data based on the number of daily incident cases by date of report. It should be noted that West Virginia’s COVID-19 declaration of emergency was terminated on January 1, 2023.¹¹

Statistical language and Supplementary Materials

R version 4.3.1 and RStudio version 2023.9.0.0 statistical software were used to conduct the statistical analysis and to create figures and maps. We used the R package EpiEstim version 2.2-4 to generate R_t estimates. The online supplementary materials contain 20 files. Files S1–S9 are the R codes used to generate figures and data estimates. Files S10–S19 are the R functions used in these data files. File S20 contains Supplemental Figure 1.

Results

7-Day-Sliding-Window R_t

The statewide R_t estimation showed significant changes in reproduction numbers throughout the time series. Figure 2 presents the bootstrapped incident case count data (panel 1), estimated daily infection count (panel 2), and the 7-day sliding window R_t (panel 3) for West Virginia. At the pandemic’s start, the 7-day sliding-window R_t was estimated to be 2, dropping to 1 in early April 2020. For the rest of the time series, R_t fluctuated above and below 1, showing when the pandemic was spreading and slowing down. The number of new cases stayed consistent for the first 8 months of 2020, with the first wave occurring at the end of December and going through January 2021. From January 2021–July 2021, 1 peak in R_t was greater than 1. In the remainder of 2021, there were 2 prominent peaks greater than 1. In 2022, there were 2 peaks: 1 early in the year and 1 in May. R_t fluctuated right around 1 for the rest of the year. The estimated number of new infections had 3 prominent peaks throughout the time series. The highest number of new cases was estimated in January 2022, the Omicron wave.¹²

Policy Change R_t

The percentage change in policy change R_t across West Virginia and its regions is presented in Figure 3. Supplemental Figure 1 (Supplemental File S20) presents the statewide changes in R_t over time across all non-overlapping time windows. The first policy change date, March 24, occurred 5 days after West Virginia reported its index case (Table 1). After the stay-at-home order was implemented, the policy change R_t decreased substantially (-38.67%; 95% CrI, -57.47%, -21.78%). Six regions experienced significant decreases in R_t after the policy change, with the Clarksburg region showing the largest decrease (-39.52%; 95% CrI, -60.73%, -15.02%). Metro-Charleston, Northern, Martinsburg, Morgantown, and Wood-Jackson decreased by about 30% (Table 2).

Reopening Begins marked the start of businesses reopening in West Virginia. With restrictions, businesses could open to small crowds; most were carry-out-only options. After May 4, 2020, the state saw a 12.06% (95% CrI, 0.54%, 26.25%) increase in R_t . The

Table 1. A list in timeline order of all policy changes made by West Virginia to decrease the spread of COVID-19 March 2020–December 2020

Labels used in non-overlapping time-window R_t Policy Plots	Date (mm/dd/yyyy)	Implemented measure(s)
	03/04/2020	State of Preparedness Proclamation issued by Governor Justice. ^{27,28}
	03/12/2020	Governor Justice issues statewide visitation restrictions to all nursing homes in West Virginia. ^{28,29}
	03/14/2020	Announcement of school closure. ^{30,31}
	03/16/2020	State of Emergency Declared by Governor Justice. ^{28,32}
	03/17/2020	West Virginia's first COVID-19 case. ^{28,33}
	03/17/2020	Closure of all restaurants and bars for dine-in at 11:59PM on March 17, 2020. Establishments are allowed to continue carry out and drive-thru operations. Casinos also close at 11:59PM. ^{28,34}
	03/18/2020	Non-essential state employees are allowed to work at home. Gyms and recreational facilities closed. Regional Departments of Motor Vehicles are closed. ^{28,35}
	03/18/2020	Second confirmed COVID-19 case. ³⁶
	03/19/2020	Executive Order (No. 4-20) ³⁷ providing unemployment benefits for those who are unable to work due to COVID-19. ³⁸
	03/20/2020	Executive Order (No. 6-20) ³⁹ ordered all nail salons, hair salons, and barbershops to close at 12:00 AM on March 20, 2020.
A	03/23/2020	Stay at Home Order implemented. ^{28,40} Executive Order (No. 9-20) ⁴⁰ stated that at 8:00PM of March 23, 2020, residents of WV are to stay at home in their place of residence unless they are performing essential activities.
	04/03/2020	Executive Order (No. 20-20) ⁴⁴ issued that expands March 23, 2020 Stay at Home Order for Berkeley, Jefferson, and Morgan counties. ⁴¹
	04/04/2020	Executive Order (No. 21-20) ⁴⁵ issued that expands March 23 Stay at Home Order for Harrison, Kanawha, and Monongalia counties. ⁴⁶
	04/17/2020	Executive Order (No. 27-20) ⁴⁷ issued, making it the first state to test every nursing home resident and staff member for COVID-19.
	04/27/2020	Governor Justice announces the "West Virginia Strong-The Comeback" (WVSC) plan allows businesses to begin opening weekly in phases starting on April 30, 2020. ^{42,48}
	04/30/2020	Phase 1 of the WVSC plan. Beginning Thursday, April 30, elective medical procedures, daycares, and outpatient care operations resume, provided proper testing procedures are in place. ^{42,48}
	05/04/2020	Phase 2 of WVSC allows small businesses with fewer than 10 employees; restaurants with takeaway service or outdoor dining; religious entities and funeral homes; and barbershops, hair salons, nail salons, and pet grooming services to begin operations on May 4. ^{42,48}
B	05/04/2020	Safer at Home Order (No. 32-20) takes effect, replacing the original Stay at Home Order. ^{49,50}
	05/11/2020	Phase 3 of WVSC plan allows wellness centers operated by or with West Virginia Licensed Healthcare providers and drive-in movie theaters to open on May 11. ^{42,48}
		Phase 3 of WVSC plan allows outdoor guided fishing and rock climbing to open on May 15, 2020. ^{42,48}
	05/18/2020	Phase 4 of WVSC plan allows fitness centers, gymnasiums, recreational centers, and sports training facilities to open on May 18. ^{42,43,48}
	05/21/2020	Phase 4 of WVSC plan allows indoor dining at restaurants, retail stores, state park campgrounds for in-state residents, Hartfield McCoy Trail System, outdoor recreation rentals, outdoor motor sport and power racing (without spectators), tanning businesses, white water rafting, zip lining, and indoor malls to reopen on May 21. ^{42,48}
	05/26/2020	Phase 5 of WVSC plan allows state park cabins and lodges to reopen for in-state residents. Bars are allowed to reopen at 50% capacity. Museums, visitor centers, and zoos also open. ^{42,48}
	05/27/2020	All inmates and employees of correctional facilities must now be tested for COVID-19. ^{28,51}
	05/30/2020	Phase 5 of WVSC plan allows spas, massage businesses, swimming pools, bowling alleys, pool halls, roller rinks, and other indoor amusement parks to reopen. ^{42,48}
	06/05/2020	Public gatherings can now increase from 25 to 100 people. ^{28,52}
	06/05/2020	Phase 6 of WVSC plan allows casinos, movie theaters, and bingo halls to reopen. ^{42,48}
	06/08/2020	Phase 7 of WVSC plan allows low contact youth sports, little league sports practices, and all remaining indoor sports centers to commence. Sanctioned athletic and band summer training programs are allowed to commence provided they meet West Virginia Secondary School Activities Commission's guidelines (WVSSAC). ^{42,48}

(Continued)

Table 1. (Continued)

Labels used in non-overlapping time-window R_t Policy Plots	Date (mm/dd/yyyy)	Implemented measure(s)
	06/10/2020	Phase 7 of the WVSC plan allows private campgrounds, state park campgrounds, cabins, and lodges to open for out of state residents. Out of state residents may not stay longer than 7 days. ^{42,48}
	06/15/2020	Phase 8 of WVSC had no additional re-openings. ^{42,48}
	06/22/2020	Phase 9 WVSC allows youth sports games, outdoor sporting events, outdoor equestrian events, and outdoor motor racing events to have spectators. Youth summer camps reopen. In-person high school graduation ceremonies may commence assuming the WV Dept. of Education guidelines are followed. ^{42,48}
C	07/07/2020	Statewide Indoor Face Covering Requirement. ^{54,73} Effective as of 12:01 AM on July 7, 2020 Executive Order (No. 50–20) ⁷³ requires that: All individuals age 9 or over in the state of WV must wear adequate face coverings when in confined, indoor spaces, other than within one's own residents or when actively engaged in the consumption of food and/or beverages, and when adequate social distancing from other individuals who do not reside in same household is not possible.
	07/10/2020	Phase 10 of WVSC allows fairs, festivals, outdoor open-air concerts, and similar events to commence. ^{42,48,55}
	07/14/2020	Fairs, festivals, outdoor open-air concerts, and similar events are re-closed. Social gatherings limited to 25 people. ⁵⁶
	07/14/2020	Executive Order (No. 52–20) ⁵⁷ issued closing all bars in Monongalia county. Service directly from bars is prohibited in restaurants and hotels with “bar areas.”
	07/25/2020	Executive Order (No. 56–20) ⁵⁸ issued that allows public and private pre-K–12 schools to operate for purposes of facilitating or conducting distance learning, holding, or participating in graduation ceremonies or other extracurricular activities, and/or performing other essential functions provided that such educational institutions may also resume in-person operations no sooner than September 8, 2020, provided that social distancing and other safety practices are followed. Executive order allows colleges and universities to resume in-person instruction and other operations, provided guidelines are met.
	08/13/2020	Executive Order (No. 61–20) ⁵⁹ issued that prohibits nursing home visits except compassionate care due to end of life or deteriorating conditions.
	08/21/2020	The West Virginia COVID–19 Dashboard updated to include a County Alert System which posts the average number of COVID–19 cases per 100 000 in colors red (25+ cases per 100 000), orange (10–24.9 cases per 100 000), yellow (3.1–9.9 cases per 100,000), and green (3 cases per 100 000). It was announced on August 21, 2020 that school status and nursing home visitation will be determined by the color of the county. ^{28,74}
	08/31/2020	Monongalia bars are allowed to reopen if protocol is followed. ²⁸ Student-athletes of orange counties, Fayette, Kanawha, and Logan are allowed to participate in competitions if their entire team tests negative for COVID–19. School-affiliated marching bands and auxiliary groups can also perform if the entire group tests negative. ⁷⁵
	09/02/2020	Executive Order (No. 65–20) ⁷⁶ issued re-closing Monongalia bars.
	09/04/2020	In preparation for reopening schools, an Executive Order (No. 68–20) ⁷⁷ was released saying that all schools, both public and private pre-K through grade 12, must follow the WVDHHR's County Alert System county-by-county color-coded system to ensure that safety requirements are met for in-person instruction and/or athletic and extracurricular activities.
D	09/08/2020	Schools reopen across WV. ^{53,78,79} The school board can choose online or in-person instructional methods. In-person instruction was resumed in 46 of 55 counties.
	09/11/2020	Governor Justice announces that going forward, all schools in orange counties when the official County Alert Map weekly report is made on Saturdays at 5:00PM are moved to online instruction. ⁸⁰
	09/16/2020	New color announced for County Alert System. Colors are as follows: green (3 and fewer cases per 100 000 OR 3% or less positivity rate), yellow (3.1–9.9 cases per 100 000 OR 4% or less positivity rate), gold (10–14.9 cases per 100 000 OR 5% or less positivity rate), orange (15–24.9 cases per 100 000 or 8% or less positivity rate), red (25+ cases per 100 000 and greater than 8% positivity rate). ^{28,81} As of September 16, 2020, any county in the gold category can move to in-person instruction with restrictions that include face coverings at all times for grades 3–12. Extracurricular activities and competitions may occur within the same county or within other gold counties.
	09/16/2020	Executive Order (No. 70–20) ⁸² issued reducing the size of social gatherings from 25 to 10 people in red, orange, and gold counties. Travel sports teams are prohibited from bringing players or spectators together for games, practices, and/or competitions in red, orange, and gold counties. ²⁸
	09/21/2020	Gov. Justice announces “Aggressive Testing” is to take place in all red and orange counties. The Aggressive Testing strategy is that whenever a county moves to orange or red there will be free COVID–19 testing set up in that county within 24 hours and stay there until case numbers improve.

(Continued)

Table 1. (Continued)

Labels used in non-overlapping time-window R_t Policy Plots	Date (mm/dd/yyyy)	Implemented measure(s)
		Any county in gold counties will have at least 1 free testing event per week until case numbers improve. ^{28,83}
	09/23/2020	Gov. Justice announces all WV counties are out of red status. ^{28,84}
	09/23/2020	Executive Order (No. 71–20) ⁸⁵ allowing schools to reopen in person is amended to enhance safety measures for private and Christian schools, including full testing of staff and students to hold in-person instruction.
	10/06/2020	Executive Order (No. 74–20) ⁶⁰ allowing outdoor live music performances and certain indoor music performances to resume if safety guidelines are followed. Guidelines state for outdoor venues that crowd sizes are restricted to 25% of the venue's full capacity or 250 individuals, whichever is less. All other previously stated restrictions for hosting live performances remain in effect. ⁶¹
	10/13/2020	Executive Order (No. 75–20) ⁶² allowing Monongalia County bars to reopen if safety guidelines are followed.
	10/16/2020	Executive Order (No. 76–20) ⁶³ signed that allows WV military personnel directly involved in pandemic response who have been unable to use annual leave due to the emergency situation and are subject to losing annual leave to have any unused annual leave time carry over from the 2020 calendar year to the end of the 2021 calendar year.
	11/13/2020	Executive Order (No. 78–20) ⁶⁴ issued which extends Thanksgiving break for public and private schools until December 2, 2020. All schools, public and private, should implement remote learning activities beginning November 26, 2020 through December 2, 2020.
	11/13/2020	Executive Order (No. 79–20) ⁶⁵ requires all doctors, staff, and residents of nursing homes and assisted living facilities to take a COVID–19 test twice a week.
	11/13/2020	Executive Order (No. 80–20) ⁶⁶ issued that postpones the start date of all youth winter sports teams and leagues until, at the earliest, January 11, 2021. Includes without limitation basketball, swimming, wrestling, and cheerleading are prohibited from bringing players and/or spectators into a common area within this state and that no practices, games, or competitions may be held until January 11, 2021.
	11/13/2020	All band festivals scheduled for spring of 2021 are canceled. ^{28,67}
E	11/14/2020	Effective as of November 14, 2020, the indoor face covering requirements broadened statewide in preparation for the holiday season as per Executive Order (No. 77–20). ⁶⁸ The previous indoor face covering requirements still stand with the addition of businesses and organizations that invite the public into their facility must now require compliance with terms of this order and post adequate signage notifying patrons that this order will be enforced on their premises.
	12/04/2020	Gov. Justice releases an initial allocation plan for the COVID–19 vaccine. ^{28,69} Phase 1 of the WV COVID–19 Vaccination Program will include healthcare workers, long-term care facility residents and staff, and community infrastructure and emergency response teams (public health officials and first responders).
	12/11/2020	WV COVID–19 Vaccine Program updated. ⁷⁰
	12/14/2020	First COVID–19 Vaccination in WV. ^{28,71}
	12/16/2020	Gov. Justice releases plans for Phase 2 of WV COVID–19 Vaccination Program. ^{28,72}

Clarksburg region experienced a 41.03% (95% CrI, 11.50%, 89.31%) increase, Morgantown had a 30.5% (95% CrI, 7.20%, 63.22%) increase, the Northern region increased by 28.96% (95% CrI, 4.83%, 66.21%), and Metro-Charleston increased by 20.87% (95% CrI, 6.75%, 43.80%). The Eastern, Western, and Martinsburg regions had decreased R_t , which were not statistically significant.

The indoor face-covering mandate was implemented 9 weeks after reopening began (Table 1). This mask mandate was designed to slow the spread of the SARS-CoV-2 virus between people. After this mandate in early July, policy change R_t decreased in West Virginia (-10.57%, 95% CrI, -18.92%, -3.24%). Metro-Charleston, Morgantown, Southern, Northern, and Clarksburg saw noticeable decreases in R_t , while the rest saw negligible changes.

In September 2020, West Virginia opened all schools up to in-person instruction with restrictions. The state saw a 12.41%

(95% CrI, 4.01%, 18.93%) increase in policy change R_t , which was similar to what was seen in the Southern region. The Northern region had an increase of 33.52% (95% CrI, 17.83%, 56.14%).

Lastly, after schools transitioned back to online learning in November 2020, policy change R_t decreased in West Virginia (-9.41%, 95% CrI, -15.42%, -3.20%). Martinsburg, Southern, and Western regions had decreases of a magnitude close to 10%, with Wood-Jackson and the Northern region having over 15% decreases. The rest of West Virginia did not see a significant increase or decrease in R_t through the end of 2020.

Incidence Rate Ratio

The relative burden of incident cases by region and year is presented as IRR with the state as the referent (Table 3, Figure 4). The IRRs of

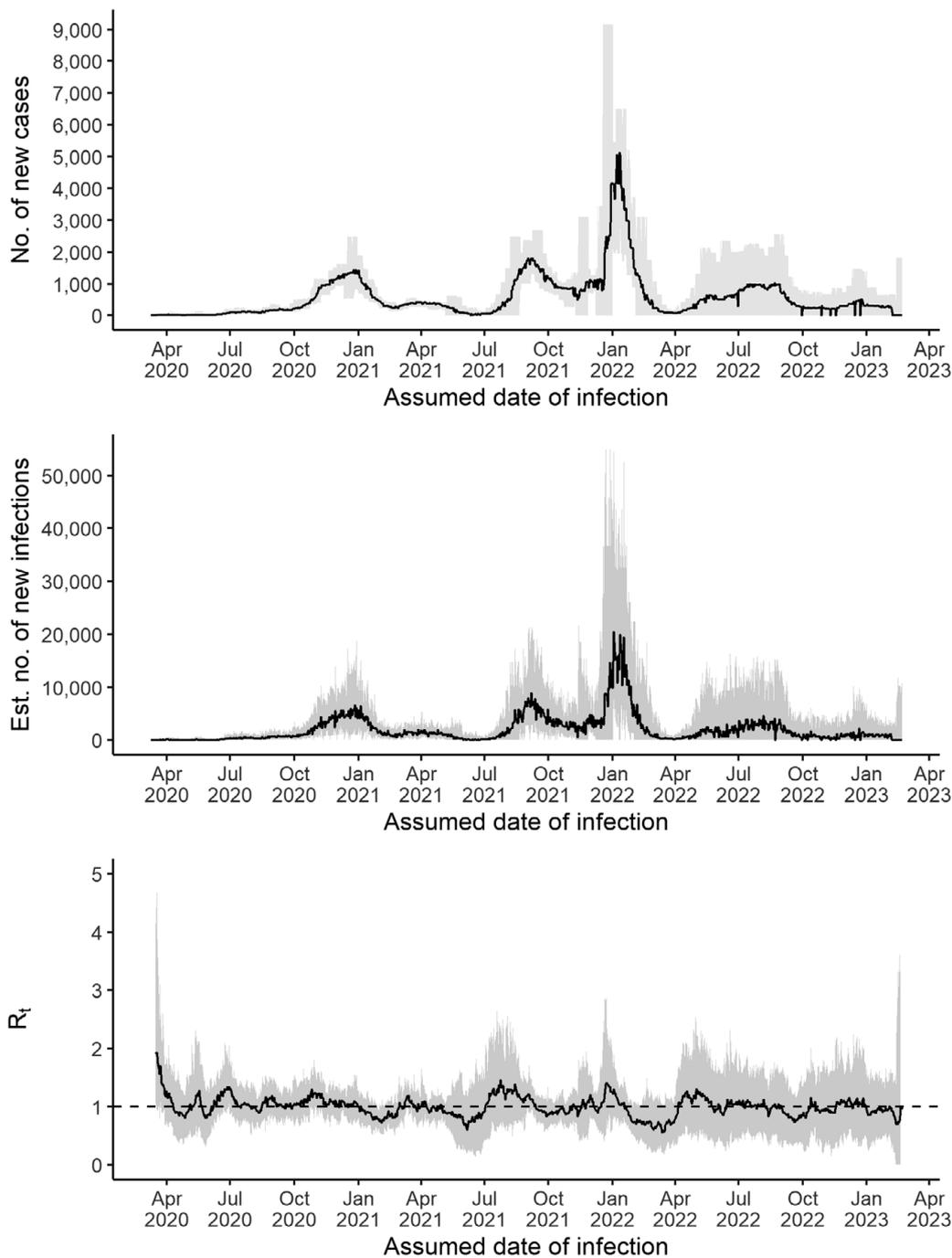


Figure 2. Panel 1 is the number of new cases in West Virginia throughout the time series with credible intervals. Panel 2 is the estimated number of new infections for the time series with a credible interval. Panel 3 presents the 7-day sliding window R_t estimates (black line) and its 95% credible interval (grey areas).

Metro-Charleston (Region A) were only slightly greater or less than 1, indicating the epidemic in Metro-Charleston was driving that of the state. Clarksburg (Region B) had an IRR of 0.822 (95% Confidence Interval (CI), 0.8, 0.844) in 2020 but had $IRR > 1$ in the following years. The Eastern (Region C), Western (Region D), and Southern (Region F) regions showed decreases in IRR from higher values in 2020 to lower values in 2021 and 2022. For example, the Western region decreased from an IRR of 1.86 (95% CI, 1.814, 1.900) in 2020 to 1.161 (95% CI, 1.143, 1.179) in 2022. It should be

noted that the Western region consistently had $IRR > 1$ from 2020–2022. Wood-Jackson (Region I) had the highest IRR, peaking in 2021 at 1.961 (95% CI, 1.937, 1.984). Wood-Jackson had around 19.6 regional cases per every 10 cases seen throughout the state. Morgantown (Region H) had small fluctuations in IRR, remaining around 0.55 in 2020 and 2022 with a peak in 2021 of 0.73 (95% CI, 0.718, 0.743). Martinsburg (Region G) saw a case burden consistently lower than the state by 5% to 18% in 2020–2022. The Northern region (Region E) performed the best throughout the time series,

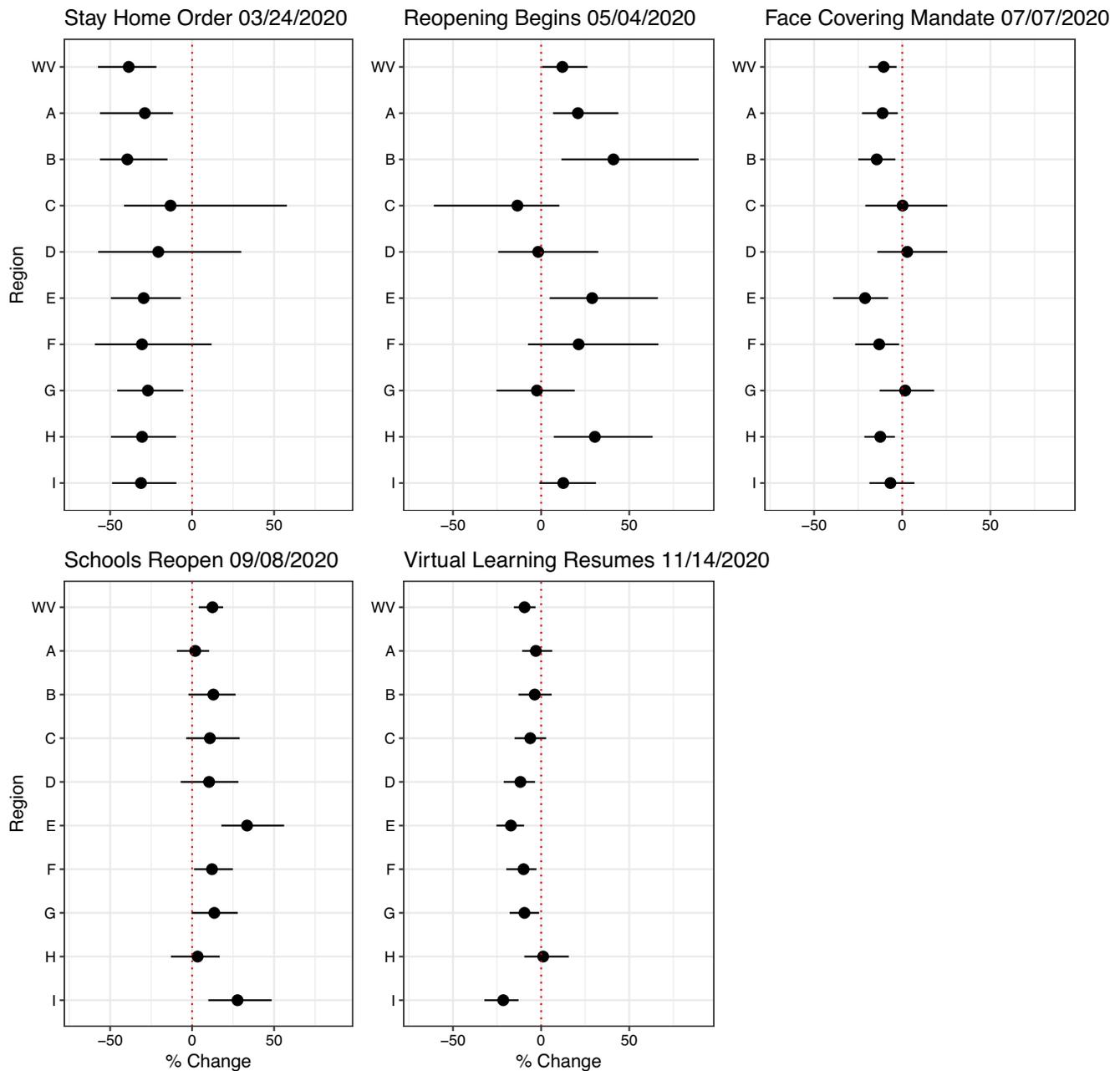


Figure 3. This figure displays the percentage change in R_t value with each policy implementation between each of the non-overlapping time windows. The figures display the Stay-at-Home Order, Reopening Begins, Indoor Mask Mandate, Schools Reopen, and Virtual Learning Resumes. A=Metro-Charleston, B=Clarksburg, C=Eastern, D=Western, E=Northern, F=Southern, G=Martinsburg, H=Morgantown, I=Wood-Jackson.

with its lowest IRR in 2020 at 0.323 (95% CI, 0.316, 0.330). For every 10 new cases statewide, there were 3 new cases seen in the Northern region.

Discussion

In this study, we analyzed COVID-19 epidemiology in West Virginia by completing a threefold analysis: (i) describing the changes in COVID-19 transmission potential from March 2020-February 2023 through 7-day sliding-window R_t estimation, (ii) estimating the effect of non-pharmaceutical interventions and public health policy changes in 2020 via percentage changes in policy change R_t ,

and (iii) identifying regional variation in case burden through IRR estimation by region using statewide case count as the reference group. Tracking R_t fluctuations during the pandemic illustrates the epidemic trends of SARS-CoV-2 throughout the population. The R_t allows us to visualize the disease's transmissibility. West Virginia's R_t peaked with the index case in March 2020, and a steep decline showed how the number of new cases stayed low until October 2020, when R_t steadily increased through mid-November 2020 (Figure 2 Panels 1,3).

The findings of this research are supported by similar studies conducted in other states across the US. West Virginia, located in the South Atlantic region with Georgia, South Carolina, Delaware, and several other states, experienced similar peaks, changes, and

Table 2. Percentage change and 95% credible interval (CrI) in Policy Change R_t after each policy change, in West Virginia and its regions, in 2020

Region	% change (95% CrI)				
	Stay at Home Order (03/24/2020)	Reopening Begins (05/04/2020)	Indoor Face Covering Mandate (07/07/2020)	Schools Reopen (09/08/2020)	Virtual Learning Resumes (11/14/2020)
Statewide	-38.67 (-57.47, -21.77) *	12.06 (0.54,26.25) *	-10.57 (-18.92, -3.24) *	12.41 (4.01,18.93) *	-9.41 (-15.42, -3.20) *
Charleston	-28.84 (-56.20, -11.68) *	20.87 (6.75,43.80) *	-11.19 (-22.85, -2.53) *	1.89 (-9.30,10.36)	-2.98 (-10.75,6.30)
Clarksburg	-39.52 (-60.73, -15.02) *	41.03 (11.50,89.31) *	-14.50 (-24.98, -3.89) *	12.95 (-2.25,26.52)	-3.63 (-12.84,5.95)
Eastern	-13.17 (-41.56,57.80)	-13.46 (-60.88,10.36)	0.19 (-20.95,25.60)	10.83 (-3.64,28.99)	-6.17 (-15.08,2.85)
Western	-20.65 (-57.31,29.97)	-1.66 (-24.32,32.41)	2.83 (-14.14,25.57)	10.34 (-6.97,28.26)	-11.76 (-21.21, -3.45) *
Northern	-29.56 (-49.56, -6.88) *	28.96 (4.83,66.21) *	-21.11 (-39.24, -8.00) *	33.52 (17.83,56.14) *	-17.13 (-25.35, -9.64) *
Southern	-30.59 (-59.32,11.85)	21.29 (-7.46,66.52)	-13.10 (-26.70, -1.79) *	12.11 (1.16,24.89) *	-9.97 (-19.78, -2.66) *
Martinsburg	-27.00 (-45.67, -5.37) *	-2.39 (-25.33,19.06)	1.67 (-12.85,18.09)	13.53 (-0.38,27.83)	-9.46 (-17.86, -1.13) *
Morgantown	-30.53 (-49.51, -9.80) *	30.50 (7.20,63.22) *	-12.47 (-21.45, -4.20) *	3.35 (-12.96,16.81)	1.16 (-9.51,15.70)
Wood-Jackson	-31.19 (-48.85, -9.59) *	12.56 (-0.97,31.08)	-6.72 (-18.60,6.92)	27.71 (9.90,48.49) *	-21.48 (-32.22, -12.80) *

CrI, credible interval. The dates were indicated in the mm/dd/yyyy format. *The 95% CrI does not include 0 (equivalent to $P < 0.05$) indicating that the null hypothesis that the percentage R_t change equals 0 can be rejected.

Table 3. This table displays the incidence rate ratio (IRR) estimates of each region in West Virginia across 2020, 2021, and 2022, using the statewide incident case rate as the reference group. There were 3 Poisson regression models, 1 for each year

Region	2020 IRR (95% CI)	2021 IRR (95% CI)	2022 IRR (95% CI)
Metro-Charleston	0.971 (0.958,0.985) *	0.980 (0.972,0.988) *	1.050 (1.043,1.058) *
Clarksburg	0.822 (0.800,0.844) *	1.104 (1.089,1.119) *	1.079 (1.066,1.093) *
Eastern	0.685 (0.667,0.702) *	0.550 (0.541,0.559) *	0.524 (0.516,0.532) *
Western	1.860 (1.814,1.900) *	1.190 (1.170,1.211) *	1.161 (1.143,1.179) *
Northern	0.323 (0.316,0.330) *	0.395 (0.390,0.400) *	0.351 (0.347,0.355) *
Southern	0.804 (0.785,0.824) *	0.637 (0.626,0.647) *	0.656 (0.646,0.665) *
Martinsburg	0.857 (0.832,0.869) *	0.824 (0.813,0.837) *	0.941 (0.931,0.951) *
Morgantown	0.541 (0.524,0.560) *	0.730 (0.718,0.743) *	0.593 (0.583,0.603) *
Wood-Jackson	1.903 (1.864,1.942) *	1.961 (1.937,1.984) *	1.809 (1.789,1.830) *

* $P < 0.001$. CI, Confidence interval. IRR, Incidence rate ratio.

values of R_t throughout the first year of the COVID-19 pandemic.¹³⁻¹⁵ In West Virginia, a peak in R_t was observed in early July 2020, followed by a decline after the implementation of the mask mandate on July 7, 2020. The R_t dropped below 1 in May, June, and September 2020. These fluctuations in R_t could be associated with a false sense of security as case numbers decline, leading to increased social activity. In early May 2020, new cases remained constant, and R_t was low. However, once Governor Justice initiated “The Comeback” campaign, which began opening businesses, R_t increased and then dropped in June 2020. The increase in cases leading up to July likely influenced the decision to implement the mask mandate in July 2020. Following the

mandate, R_t fluctuated around 1 until it dipped below 1 in September 2020, potentially supporting the reopening of schools.

The policy changes that had the most significant impact on R_t estimation were primarily those implemented during the first 3 months of the pandemic in West Virginia. The state experienced significant percent changes in R_t for all 5 policy changes, contrasting with a study conducted in Alabama, Louisiana, and Mississippi, where substantial changes in R_t were seen with each policy change. These states implemented their stay-at-home order in early May and saw changes up to -20% in R_t , compared to West Virginia’s -38% (95% CrI, -57.47%, -21.77%).^{15,16} Both of these states observed significant decreases in R_t following the stay-at-home

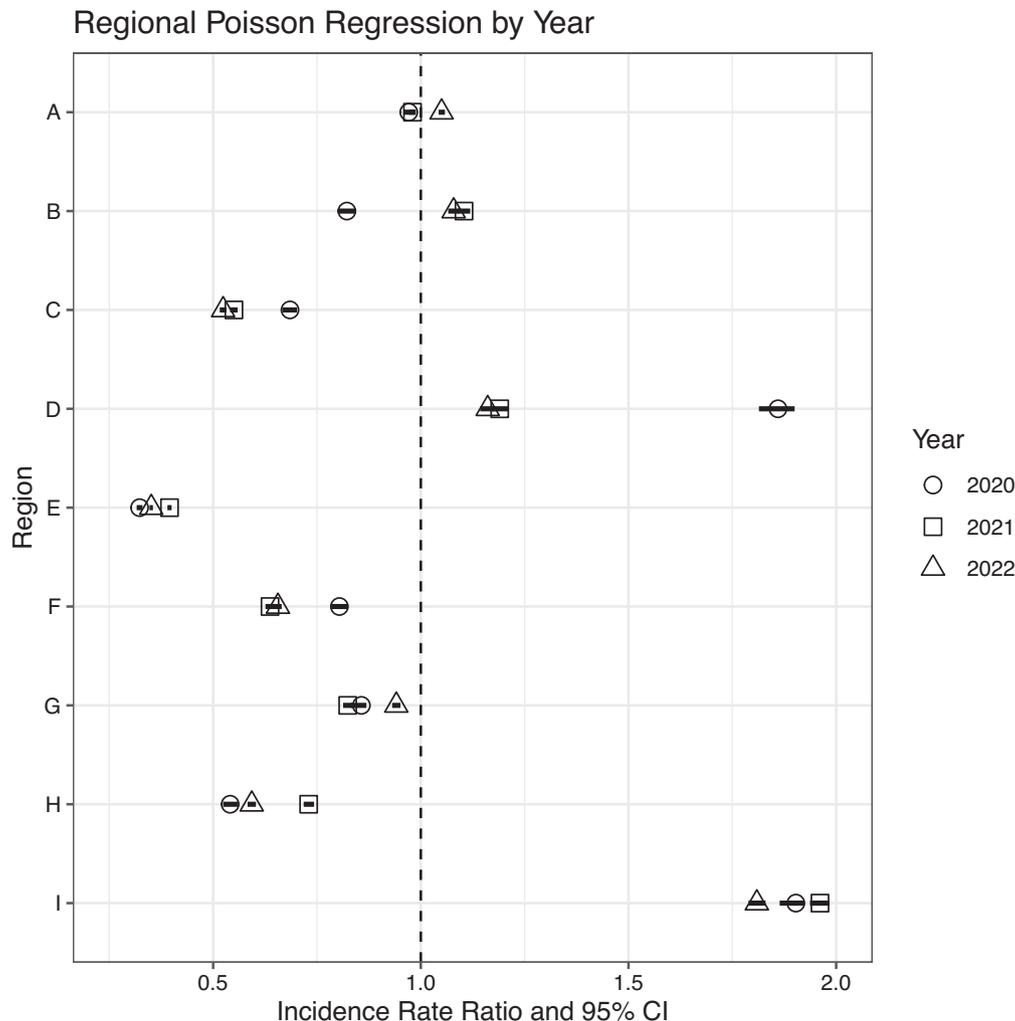


Figure 4. This figure displays the incidence rate ratio (IRR) from each region, with the incidence rate of West Virginia as the referent. The year is indicated by the symbol shape. 95% Confidence Intervals (CI) are indicated by the black bar. Each region is indicated by the following alphabet. A=Metro-Charleston, B=Clarksburg, C=Eastern, D=Western, E=Northern, F=Southern, G=Martinsburg, H= Morgantown, I=Wood-Jackson.

orders. Seven states in the US did not implement stay-at-home orders at the beginning of the pandemic.¹⁷ Of these, 4 have similar R_t estimation studies. North Dakota and Wyoming saw no significant change in R_t after their first policy change. At the same time, South Dakota experienced an increase in R_t following the announcement of the state of emergency.¹⁸ Arkansas, however, saw a change in R_t by -53% after closing school on March 17, 2020, successfully maintaining control of the pandemic with its first policy change.¹⁵ These variations indicated that implementing true stay-at-home orders, compared to other policy changes, significantly increases the likelihood of maintaining control of the pandemic, especially early on. Arkansas, for example, had social distancing guidelines in place, but the comparison across these states suggests that stricter stay-at-home orders were more effective in managing the early pandemic when vaccine was not available.

Politis *et al.* reported differences in R_t values following policy changes in the Appalachian region of Kentucky, noting a higher initial R_t compared to the statewide R_t observed in West Virginia after the index case in March 2020. This suggests an opportunity to examine the geographical variation in response to public health policies throughout the Appalachian region.¹⁵ Further studies

should explore comparisons between these regions and consider the demographics of their populations.

Regionally, increases and decreases in R_t matched the statewide data in West Virginia, with no outliers or conflicting data observed. While some changes were statistically insignificant, the northern region stood out as the only area where every policy change resulted in a significant percentage increase or decrease in R_t . After schools reopened in September 2020, 3 regions experienced statistically significant percent increases in policy change R_t . These were Northern, Southern, and Wood-Jackson. Moreover, when schools resumed virtual learning in November, Western and Martinsburg regions joined them in significant decreases in policy change R_t estimates.

Metro-Charleston, Clarksburg, and Morgantown all saw changes in policy change R_t for the first 3 policy changes; however, in the last 2, they did not see a significant percent change. According to a retrospective cohort study, schools opening and going online had regionally diverse results when comparing increases in cases across the US.¹⁹ Ertem *et al.* found no statistically significant difference in incidence in different counties that had remote learning methods or in-person instruction.¹⁹ The variability in this

national analysis provides speculation as to why regionally, there was not a large difference in R_t observed for these counties when looking at the impact of in-person instruction on virtual learning models.

To gain a better understanding of how the COVID-19 pandemic impacted the regions, IRRs were calculated by region and year (2020, 2021, and 2022), and Poisson regression was used to evaluate if the case burden (case count per person-time) was statistically significantly different from the state overall. The incidence rate of every region was significantly different from the state across the entire time series. The Metro-Charleston region had a statistically significant IRR; however, the effect size was small because the incidence rate of the state was similar to the region (IRR₂₀₂₀ = 0.971 (0.958,0.985), IRR₂₀₂₁ = 0.98 (0.972,0.988), IRR₂₀₂₂ = 1.05 (1.043,1.058)). Given that the Metro-Charleston region (location of the state capital) contains 33.16% of the West Virginia population, it helps explain why this region's incidence rate is the closest to the statewide data as it hosts a large proportion of the state's population.

The Wood-Jackson region experienced an incidence rate that was twice that of the state from 2020 through 2022 (IRR₂₀₂₀ = 1.903 (1.864,1.942), IRR₂₀₂₁ = 1.961(1.937,1.984), IRR₂₀₂₂ = 1.809 (1.789,1.830)) (Figure 4). This region contains 6.24% of West Virginia's population, the second smallest region in the study. Many factors can explain why this region had so many cases. Two of the most populated cities in West Virginia are in Wood County, and Jackson County's largest city has 3900 people.²⁰ These regions are primarily rural except for 2 or 3 larger cities with a central location that hosts a large majority of essential businesses. When 2 or 3 cities host grocery stores, gas stations, and workplaces for the rural community, it creates opportunities for human interaction and disease transmission.

In contrast, the Northern region had an incidence rate that was 2/3 lower than the state's incidence rate (IRR₂₀₂₀ = 0.323(0.316,0.330), IRR₂₀₂₁ = 0.395(0.390,0.400), IRR₂₀₂₂ = 0.351(0.347,0.355)). Also known as the "Northern panhandle of West Virginia," this region is in proximity to 2 US cities with populations over 300 000.²¹⁻²³ This region contains 31.4% of the population of West Virginia. The Northern region had a much better IRR than any other West Virginia region. A closer examination of what contributed to the Northern region's better IRR would provide valuable insights into effective public health policy implementation in large populations.

The actions set in place by Governor Justice impacted West Virginia's case count for the entirety of the pandemic. The first noteworthy wave of new infections was seen in October 2020. This 7-month delay in cases was crucial in providing better control over the COVID-19 pandemic. The mask mandate also slowed the transmission of the virus by almost 11%. This aided in decreasing transmission again by slowing the ability for large virus particles to infect susceptible individuals from the air.

The evaluation of geographical differences across the state highlights how examining the state more closely can reveal patterns that R_t values alone do not show. Future research may reveal what makes these 9 regions vary substantially in incidence rate from the state. These differences have the potential to provide strong tactics that can cater to economically, socially, and demographically different populations. Mitigating the negative impacts of the pandemic was seen in West Virginia from the swift implementation of state-wide policy changes by Governor Justice. The way that R_t fluctuated above and below 1 throughout the time series showed that West Virginia had periods of control over the pandemic and periods where intervention was necessary. Timing these moments

is essential to maintaining control over a pandemic, and this evaluation contributes to the evidence for the most impactful public health interventions.

Limitations

There are limitations in this study. First, the irregularity of reporting in public health surveillance was reflected in the negative daily incident case count in the publicly available aggregated daily case count data, which had to be corrected. We further addressed the uncertainty issue of reporting irregularity by non-parametric bootstrapping of incident case count data. Second, it was suggested that only 1 in 4 COVID-19 infections were reported as cases.⁹ This underreporting phenomenon was attributed to asymptomatic and mildly symptomatic infections, with which the patients might not get tested. We addressed the underreporting issues using a Poisson-distributed multiplier to estimate the daily incidence infection count. Third, we shifted the time series of reported case count by 9 days to approximate the date of infection from the date of report, given a mean incubation of 6 days and a median of 3 days in the lag from symptom-onset to a confirmed case report.⁸

Fourth, we used the parametric instantaneous reproduction number method in the R package EpiEstim to estimate R_t . This method requires the users to specify the parameters of a known serial interval distribution as a proxy for the generation interval distribution. However, it is known that the COVID-19 serial interval may change over time due to public health interventions.^{24,25} Fifth, the EpiEstim method only represents the uncertainty in the serial interval distribution in the uncertainty bounds of R_t estimates. In this study, we represent other sources of uncertainty by applying non-parametric bootstrapping and Poisson-distributed multipliers to the case count data before applying the EpiEstim R_t estimation. Sixth, we used a non-overlapping time window between policy changes to estimate policy change R_t and its percentage change after a policy change. This method is subject to arbitrariness as the authors had to determine which policy change dates should be chosen as the cut-off points. Seventh, it was assumed that the transmission potential was stable over the period for the policy change R_t , given that a specific package of non-pharmaceutical interventions was implemented. However, people's compliance with public health interventions and policies might change over time.²⁶ We did not have data to represent such potential changes. Eighth, given that aggregate data were used, no data pertinent to individual-level characteristics, e.g., age, was available. Such confounding factors cannot be adjusted. Ninth, this is an ecological analysis. Thus, the ecological fallacy is possible. That said, ecological analysis is an appropriate study design for our study given our research question. Tenth, it was out of the scope of this paper to analyze other social determinants of health at the aggregate level.

Conclusions

Across the state of West Virginia, significant decreases in R_t were observed for the stay-at-home order, mask mandate, and when schools resumed virtual learning. These trends were also reflected across regions, and although no specific trends were seen across smaller or larger regions, Metro-Charleston did reflect significant fluctuations in R_t in the first 3 months of the pandemic. The case burden varied significantly by region in the state as reflected by IRRs substantially larger than or smaller than 1, indicating a large difference in incidence rate between the statewide rate and each of the

regions (except Metro-Charleston). Clarksburg's incidence rate was lower than the statewide rate in 2020, but higher in 2021 and 2022. Our IRR results suggest geographical variation in case burden in West Virginia.

Supplementary material. The supplementary material for this article can be found at <http://doi.org/10.1017/dmp.2025.49>.

Data availability statement. COVID-19 data analyzed in this project are publicly available at the COVID-19 Data Repository by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University.

Author contribution. AAB and XH served as co-first authors; DAA, SD, WSK, OO, and OAS served as co-second authors; AAB: Conceptualization, Study Design, R Code Writing, Data Analysis, Manuscript Writing, and Editing; XH: Conceptualization, Study Design, R Code Writing, Data Analysis, Manuscript Writing, and Editing; DAA: R Code Writing, Data Analysis, Manuscript Writing, and Editing; SD: R Code Writing, Data Analysis, Manuscript Writing, and Editing; WSK: R Code Writing, Data Analysis, Manuscript Writing, and Editing; OO: R Code Writing, Data Analysis, Manuscript Writing, and Editing; OAS: Data Analysis (Retrieval of policy information), Manuscript Editing; JS: Study Design, Manuscript Editing; JK: R Code Writing, Manuscript Editing; KOK: Manuscript Editing; GH: Manuscript Editing; ICHF: Conceptualization, Study Design, R Code Writing, Manuscript Writing, and Editing

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