Population immunity to SARS-CoV-2 in US states and counties due to infection and vaccination, January 2020- November 2021

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NOTE: This preprint reports new research that has not been certified by peer review and should not be used to guide clinical practice.
Key points

**Question:** How have SARS-CoV-2 infection and COVID-19 vaccination contributed to population-level immunity against SARS-CoV-2 in US states and counties over 2020-2021?

**Findings:** The estimated percentage of the US population with effective protection against infections by the prevalent distribution of SARS-CoV-2 variants as of October 31, 2021 was 49.9% (95%CrI: 45.4%-56.6%), and ranged between 37.2% (95%CrI: 33.4%-44.7%, Vermont) and 60.9% (95%CrI: 56.4%-66.0%, Florida) across US states.

**Meaning:** Population immunity to SARS-CoV-2 varies across the United States, but a substantial fraction of the population in every state remains susceptible to infection.
Abstract

Importance: Prior infection and vaccination both contribute to population-level SARS-CoV-2 immunity. Population-level immunity will influence future transmission and disease burden.

Objective: For each US county and state, we estimated the fraction of the population with prior immunological exposure to SARS-CoV-2 (ever infected with SARS-CoV-2 and/or received one or more doses of a COVID-19 vaccine) as well as the fraction with effective protection against infection and severe disease from prevalent SARS-CoV-2 variants, from January 1st, 2020, to October 31st, 2021.

Design, settings, participants: We used daily SARS-CoV-2 infection estimates for each US state and county, derived based on reported data on COVID-19 cases and deaths. We collated county-level vaccination coverage data and estimated the fraction of individuals both vaccinated and previously infected using the Census Bureau’s Household Pulse Survey. We used published evidence on natural and vaccine-induced immunity, and how protection wanes over time. We used a Bayesian model to synthesize evidence and estimate population immunity outcomes.

Main Outcomes and Measures: Primary outcomes were the fraction of the population with (i) a history of exposure to SARS-CoV-2 infection or COVID-19 vaccination or both, (ii) effective protection against infection, and (iii) effective protection against severe disease. We estimated outcomes for each US state and county from January 1st, 2020, to October 31st, 2021.

Results: The estimated percentage of the US population with a history of SARS-CoV-2 infection or vaccination, as of October 31, 2021, was 86.2% (95%CrI: 82.2%-93.0%), compared to 24.9% (95%CrI: 18.5%-34.1%) on January 1, 2021. State-level estimates for October 31, 2021, ranged
between 72.2% (95%CrI: 62.5%-83.3%, West Virginia) and 92.3% (95%CrI: 88.6%-96.1%, Florida). Accounting for waning, the effective protection against infection with prevalent strains as of October 31 was 49.9% (95%CrI: 45.4%-56.6%) nationally and ranged between 37.2% (95%CrI: 33.4%-44.7%, Vermont) and 59.5% (95%CrI: 56.4%-66.0%, Florida). Effective protection against severe disease was 77.4% (95%CrI: 73.7%-83.4%) nationally and ranged between 62.9% (95%CrI: 55.2%-73.3%, West Virginia) and 83.8% (95%CrI: 80.7%-88.0%, Florida).

**Conclusions and Relevance:** The fraction of the population with effective protection against SARS-CoV-2 infection and severe COVID-19 varies across the United States, but a substantial proportion of the population remains susceptible.
Introduction

As of December 17th, 2021, more than 50 million COVID-19 cases and over 800,000 COVID-19-associated deaths had been reported in the United States\textsuperscript{1,2}. The epidemic has overloaded healthcare systems, reduced economic activity, and decreased mental health\textsuperscript{3-6}. At this point in the epidemic, minimizing morbidity and mortality from COVID-19 will depend on reaching high levels of population immunity. The emergence of the Omicron variant\textsuperscript{7,8} illustrates the importance of estimates of population immunity for identifying areas of highest vulnerability, and also underscores how levels of effective protection may be reduced by continued evolution of viral variants that may evade prior immunity, as well as by waning immunity over time.

The true number of SARS-CoV-2 infections that have occurred since the start of the pandemic is unknown. Recent estimates\textsuperscript{9-12} of the percentage of the US population ever infected vary between 37\% and 62\%. Seroprevalence estimates from a nationwide convenience sample in commercial laboratories suggested that as of December 17, 2021, 24.5\% of the US population over 16 has infection-induced SARS-CoV-2 antibodies\textsuperscript{13}. The level of protection that infection confers, and the rate at which this protection wanes, are incompletely understood\textsuperscript{14-16}.

By December 17, 2021, over 240 million US residents (72.9\%) had received at least one dose of a COVID-19 vaccine\textsuperscript{1}. Reported efficacy against symptomatic infection for the three main vaccines available in the US ranged from 66\% (Johnson&Johnson) to 94\% (Pfizer and Moderna) in clinical trials\textsuperscript{17-19}. Vaccine efficacy against infection was estimated to be lower during the Delta surge compared to earlier studies, and initial data indicate further reduced efficacy against the Omicron variant\textsuperscript{7,8}. Declines in vaccine efficacy reflect a possible combination of waning immunity and increased potential for immune escape in viral variants. Vaccination appears to provide durable protection against severe disease, despite this evidence of waning efficacy\textsuperscript{20-23}. 
To evaluate the potential for continued SARS-CoV-2 transmission, it is important to estimate overall population immunity to COVID-19 achieved through both infection and vaccination. A recent study reported state-level estimates of infection- and vaccine-induced SARS-CoV-2 seroprevalence based on blood donation data, with estimates for May 2021 ranging from 63.7% in Mississippi to 91.7% in Connecticut. While these estimates provide a direct measure of seroprevalence, they may be affected by systematic differences between the blood donor population and the general population. Moreover, these data do not provide county-level estimates, nor account for waning of effective protection over time.

In this study, we used state- and county-level estimates of cumulative SARS-CoV-2 infections from a statistical model of viral transmission, natural history and diagnosis, and incorporated county-level vaccination coverage estimates corrected for reporting errors. We used survey data to estimate the joint distribution of prior SARS-CoV-2 infection and vaccination. Using this analytic framework, we estimated the population with historic SARS-CoV-2 immunological exposure (ever infected or vaccinated) for each US state and county between January 1st 2020 and October 31st 2021. Incorporating evidence on the time-course of natural and vaccine-induced immunity, we estimated effective population immunity against infection and against severe disease over time.

**Methods**

**Data**

**Infections**
We extracted time-series estimates of SARS-CoV-2 infections from a statistical model that synthesizes reported data on COVID-19 cases and deaths, accounting for under-


ascertainment and time lags associated with these reported outcomes. We imputed missing cases and deaths data for Nebraska counties after June 30th, 2021 (see eMethods).

We used these estimates to calculate cumulative infections for each U.S. state and county from January 1, 2020, to November 30, 2021. As the most recent estimates of infection rates are highly uncertain, we excluded the last month of the time-series, with the resulting estimates spanning the period January 1, 2020, to October 31, 2021. We calculated national infection estimates by summing state-level results.

**Vaccinations**

We extracted estimates from a repository reporting county-level vaccination coverage based on CDC vaccination data, adjusted for known biases and incompleteness in several states\(^{27,28}\). These estimates include weekly values for the number of county residents having received at least one COVID-19 vaccine dose (First dose), and the number of residents having completed an FDA-approved vaccine sequence (Fully vaccinated). We imputed missing First dose estimates using the observed Fully vaccinated data, and smoothed weekly data to create a daily time-series\(^{29}\) (see eMethods). We summed the time-series counts for all counties within each state to produce state-level estimates.

**Co-occurrence of infection and vaccination**

The Census Bureau’s Household Pulse Survey collects data on COVID-19-relevant beliefs and behaviors at two-weekly intervals, for individuals 18 years and older\(^{30}\). We extracted data from February 2 to August 30, 2021, to estimate the joint distribution of infection and vaccination among survey respondents. We extracted the variables had covid (Yes/No; whether a respondent has received a positive COVID-19 diagnosis), received vaccine (Yes/No; whether a respondent
has received at least one dose of a COVID-19 vaccine, state and week. Responses other than Yes or No (e.g., Unknown) were excluded (2.3% of respondents).

Estimation

History of immunity

For each US county and state, we computed the percentage immunologically exposed, defined as the percentage of the population with a prior SARS-CoV-2 infection, at least one dose of a COVID-19 vaccine, or both. We calculated values separately for individuals aged less than 12 years and those aged 12 years or older, due to differences in vaccine eligibility for these groups over the study period.

Estimates of immunity for the population aged 12 and over

Using the Household Pulse data we fit a logistic regression model to estimate the association between self-reported vaccination status and prior COVID-19 diagnosis. We operationalized this relationship as the odds ratio for reported vaccination, comparing individuals reporting a prior COVID-19 diagnosis to those reporting no prior diagnosis (see eMethods). Using these regression results we created state-specific prior distributions for the odds ratio of vaccination given prior infection status, for individuals aged 12 and older (eTable 1). This approach assumes that the odds ratio for vaccination among those with a prior undiagnosed infection is the same as for those with a prior diagnosed infection. We validated this relationship using data from the Axios-Ipsos Coronavirus Tracker31.
For each day of the time-series, we calculated the joint probability of being vaccinated and having ever been infected (full derivation in eMethods). Following the rules of probability, we computed the probability of being immunologically exposed:

\[ P(\text{immunologically exposed}) = P(\text{ever infected} \cup \text{vaccinated}) = P(\text{ever infected}) + P(\text{vaccinated}) - P(\text{ever infected} \cap \text{vaccinated}) \]

**Estimates of immunity for the population under 12 years old**

For the population under 12 years old, the percentage immunologically exposed was assumed equal to the estimated percentage ever infected, as this age group was not eligible for vaccination during the study period. We assumed infection prevalence in this age group was equal to prevalence in the overall population.

We combined the under-12 and over-12 immunity estimates in a weighted sum to obtain the percentage immunologically exposed in the full population.

**Waning of protection**

There is accumulating evidence that the protection afforded by natural infection and vaccination declines over time\textsuperscript{32-35}. We translated the latest available evidence into approximate waning curves under three scenarios: a base-case scenario (used in the main analysis), as well as pessimistic and optimistic scenarios (used in sensitivity analyses). eFigure 1 shows assumed levels of protection for each scenario. For the base-case scenario we assumed that infection or vaccination each initially confer 80% protection against infection (range for pessimistic and optimistic scenarios: 75—90%) declining to 25% (20—50%) by 12 months after exposure, and protection against severe disease starts at 95% (90—100%) and declines to 85% (65—95%) by 12 months after exposure. For individuals both infected and vaccinated we assumed protection of
90% (range 80—95%) against infection with no waning for the assumed and optimistic scenario (declining to 70% after 12 months of exposure for pessimistic scenario), and protection against severe disease starts at 95% (range 90—100%) with no waning for the base-case and optimistic scenario (declining to 80% by 12 months for the pessimistic scenario; see eMethods). Based on these assumptions we calculated the percentage *effectively protected* against infection, and against severe disease. In sensitivity analyses we estimated results for the pessimistic and optimistic scenarios.

We calculated national results by summing state-level estimates. We validated our results by comparing them to published population immunity estimates based on laboratory data from a blood-donor sample.24

**Model implementation**

We programmed the analysis using R36 and the rstan package37 (https://github.com/covidestim/covidestim/tree/immunity-waning). For state-level results, we report uncertainty using equal-tailed 95% credible intervals (95%CrI). To report uncertainty in national-level estimates we report conservative intervals that sum the upper and lower bounds of state-level intervals. County-level estimates were produced using an optimization routine9 that produces point estimates without uncertainty intervals.

**Results**

For each US state and for 3138 counties, we synthesized estimates of cumulative SARS-CoV-2 infections and estimates of cumulative COVID-19 vaccination between January 1, 2020, and October 31, 2021. We excluded 5 counties due to missing/insufficient data. In summarizing county-level results, we excluded counties with a population under 1,000 (0.9% of all counties).
By October 31, 2021, 56.2% (95%CrI: 44.8%-71.5%) of the US population was estimated to have been infected with SARS-CoV-2, with state-level estimates ranging from 23.0% (95%CrI: 15.7%-36.7%, Hawaii) to 72.7% (95%CrI: 61.9%-83.5%, Oklahoma). County-level estimates ranged from 7.0% (San Juan County, Washington) to 87.5% (Chattahoochee County, Georgia).

By the same date, 62.4% of the US population were estimated to have received at least one COVID-19 vaccine dose, with state-level coverage varying between 25.9% (West Virginia) and 78.8% (Hawaii) and county-level coverage varying between 7.6% (Taylor County, West Virginia) and 90.0% (Pitkin County, Colorado).

Based on the results of the Household Pulse Survey, individuals reporting a prior COVID-19 diagnosis were substantially less likely to report being vaccinated. The odds ratio of vaccination among individuals with a prior COVID-19 diagnosis (compared to no prior diagnosis) varied from 0.40 (95%CrI: 0.36–0.44) in Florida to 0.58 (95%CrI: 0.53–0.63) in Texas, with a national mean of 0.52 (95%CrI: 0.50–0.55).

**Estimated immunity**

On October 31, 2021, the national estimate for the population *immunologically exposed* was 86.2% (95%CrI: 82.2%-93.0%). Table 1 reports state-level estimates, which ranged from 72.2% (95%CrI: 62.5%-83.3%, West Virginia) to 92.3% (95%CrI: 88.6%-96.1%, Florida). Across counties, the percentage *immunologically exposed* on October 31, 2021, ranged from 33.5% (Sioux County, Nebraska) to 97.0% (Apache County, Arizona) (Figure 1), with an interquartile range of 77.5-85.5% (eFigure 2).

[Table 1]

[Figure 1]


**Effective protection**

Accounting for waning of immunity, the percentage of the U.S. population with *effective protection* against infection increased from 14.7% (95%CrI: 11.1%-19.8%) on January 1, 2021, to 49.9% (95%CrI: 45.4%-56.6%) by October 31, 2021. By this date the percentage of the population with *effective protection* against severe disease was estimated to be 77.4% (95%CrI: 73.7%-83.3%). At the state level, *effective protection* against infection varied between 37.2% (95%CrI: 33.4%-44.7%, Vermont) and 60.9% (95%CrI: 56.4%-66.0%, Florida) and *effective protection* against severe disease ranged between 62.9% (95%CrI: 55.2%-73.3%, West Virginia) and 83.8% (95%CrI: 80.7%-88.0%, Florida) (Table 1). Figure 2 shows how the state-level percentage *immunologically exposed,* *effectively protected* against infection, and *effectively protected* against severe disease has evolved over the course of the epidemic. For counties, the percentage of the population with *effective protection* against infection and severe disease, respectively, by October 31, 2021, varied between 13.3% and 31.1% (Sioux County, Nebraska) and 81.4% and 93.3% (Apache County, Arizona) (Figure 3).

![Figure 2](https://doi.org/10.1101/2021.12.23.21268272)

![Figure 3](https://doi.org/10.1101/2021.12.23.21268272)

**Relative contributions of prior infection and vaccination**

Nationally, 23.8% (95%CrI: 19.7%-30.6%) of the population was estimated to have been infected but not vaccinated, 29.9% (95%CrI: 21.5%-37.4%) was estimated to have been vaccinated but not infected, and 32.4% (95%CrI: 25.1%-40.9%) was estimated to have been both vaccinated and infected. The relative contributions of vaccination and prior infection varied widely across states and counties, and over time (eFigures 3 and 4). Figure 4 reports county-level
estimates of the relative contributions of vaccination and prior infection. These estimates reveal regional patterns in these different pathways to immunity. The state-population weighted regional averages of the population immunologically exposed were 87.3% in the West (21.5% only infected, 32.1% only vaccinated), 82.2% in the Midwest (24.4% only infected, 31.7% only vaccinated), 86.6% in the South (28.4% only infected, 24.5% only vaccinated), and 88.7% in the Northeast (16.3% only infected, 36.6% only vaccinated).

[Figure 4]

Validation

We re-estimated the odds ratio of vaccination given prior infection using independent survey data, allowing bi-weekly national estimates between January and June 2021 (eMethods). For the 13 survey waves included in this period, the odds ratio of vaccination given prior infection varied between 0.35 and 0.98, and the mean odds ratio across time was 0.51 (95%CrI: 0.44–0.59), very similar to the estimated national value in the main analysis (0.52; 95%CrI: 0.50–0.55). We compared our estimates of the percentage of the population immunologically exposed with blood donor seroprevalence estimates (eFigure 5). Our estimates of the percentage immunologically exposed are generally lower than the estimates of seroprevalence by Jones et al.24

Sensitivity analyses

We conducted two additional analyses to evaluate the sensitivity of our effectively protected estimates to the specification of the waning curves, with an optimistic scenario and a pessimistic scenario (eMethods and eFigure 1). In the optimistic waning scenario, the population with effective protection against infection by October 31, 2021, was 64.2% nationally, (state rang:
Effective protection against severe disease was 85.3% (state range: 66.1%-92.3%, eTable2). In the pessimistic waning scenario, the population with effective protection against infection was 36.6% nationally, (state range: 21.4%-42.8%). Effective protection against severe disease was 59.3% (state range: 45.1%-65.4%, eTable2).

**Discussion**

We analyzed the joint distribution of COVID-19 vaccination and prior SARS-CoV-2 infection in each US state and county since the beginning of the COVID-19 epidemic, and estimated how population immunity changed over this period. By October 31st, 2021, over three-quarters of the U.S. population had prior immunological exposure to SARS-CoV-2 via vaccination or infection, and half of the population retained effective protection against infection. Between states and counties there were differences in the overall level of immunity achieved, and the relative contribution of vaccination and prior infection to reaching estimated immunity levels.

To report estimates of effective protection we made assumptions about how natural and vaccine-induced immunity wanes over time. While these assumptions were based on published evidence, there is still substantial uncertainty about how immunity changes over time. Recent studies suggest that antibody titers decay rapidly in the three months following infection and more gradually thereafter\(^\text{16,39}\). However, neutralizing antibody activity has been observed up to eight months post symptom onset\(^\text{14}\), and simulation studies suggest that titers wane below 1:20 (often used to infer 50% protection) for the majority of previously infected individuals by 341 days post symptom onset\(^\text{16}\). In vaccinated individuals, antibody titers are believed to wane at similar rates\(^\text{15}\), although vaccine efficacy has been shown to remain robust in the first six months following inoculation\(^\text{22,23}\). The longer-term effects of waning antibody titers on vaccine efficacy,
and the amount of protection conferred by partial vaccination (e.g. one dose of a two-dose regimen) are still incompletely understood.

In sensitivity analyses we examined optimistic and pessimistic scenarios for how protection against infection and severe disease wanes over time, providing a range of possible values of the level for effective protection. We currently only account for waning of immunity, but escape, especially with Omicron as the potential new dominant variant, could be a more significant factor in determining population immunity beyond 2021.

Our modeled estimates rely on multiple publicly available data sources, each of which has its own limitations. For vaccination coverage, we used data from Merritt et al\textsuperscript{27,28}, which endeavors to address known biases in the CDC vaccination data. We further adjusted these vaccination data to assure that no greater than 100% of the over 12 population could have been vaccinated by the end of our study period. While most indicators suggest lower cumulative infections among children, there is evidence that contradicts this and suggests a higher seroprevalence for children compared to adults\textsuperscript{40-43}. For our infection rate estimates, we used a model which leverages case notification and COVID-19 mortality data from Johns Hopkins University and have incorporated modeled uncertainty in these estimates into our model of immunity. The model for infections assumes individuals can only be infected once, so possible reinfections and breakthrough infections amongst vaccinated individuals are not accounted for in our estimates of immunity. We estimated the relationship between prior infection and vaccination status using survey data that have been criticized for non-representativeness\textsuperscript{31}. While this relationship was confirmed in independent survey data that have been validated against external benchmarks\textsuperscript{31}, it is still possible that reporting biases could have distorted this relationship. If there is greater overlap
between vaccinated and previously infected populations, then overall population immunity will be lower than estimated in our analyses.

The COVID-19 epidemic, measures, and knowledge are changing fast. On November 1st, 2021, children 5-11 years old became eligible for vaccination, which is outside the time period of our analysis. Boosters have become widely available to the US population over 18 years of age since November 17, 2021, after a more restricted campaign starting late September 2021. The data on received booster shots is still scarce, as is evidence on the effect on waning. We also did not account for differences in waning depending on the virus variant distribution.

**Conclusions**

The fraction of the US population that has ever been infected with SARS-CoV-2 and/or received at least one dose of a COVID-19 vaccine varies between counties and states. Accounting for waning of population immunity, *effective protection* against infection in US states is between 31.4 and 43.5 percentage points lower than the percentage *immunologically exposed*.

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**Author contributions**

TC, NAM and JAS conceived and supervised the project. TC, NAM and JAS acquired funding.

FK wrote the model code, drafted the original manuscript and visualized the results. FK and MR curated the data and executed the analysis. All authors contributed to the development of the methodology, and reviewed and edited the original manuscript.

**Conflicts of interest:**

VEP has received reimbursement from Merck and Pfizer for travel expenses to Scientific Input Engagements unrelated to the topic of this manuscript. All other authors have declared that no competing interest exist.

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Table 1: Key population immunity outcomes for each US state on October 31, 2021.

| State          | Percentage ever vaccinated* | Percentage ever infected (95%CrI) | Ratio percentage vaccinated / percentage infected | Percentage immunologically exposed (95%CrI) | Percentage effectively protected against infection (95%CrI) | Percentage effectively protected against severe disease (95%CrI) |
|----------------|----------------------------|----------------------------------|--------------------------------------------------|--------------------------------------------|-------------------------------------------------------------|---------------------------------------------------------------|
| Alabama        | 50.5%                      | 70.6% (60%-82.4%)                | 0.72                                             | 88.1% (83.3%-94.1%)                         | 53.1% (49.7%-56.8%)                                         | 78.8% (74%-84.7%)                                             |
| Alaska         | 55.4%                      | 62.1% (50.6%-76.1%)              | 0.89                                             | 86.4% (80.6%-92.7%)                         | 54.1% (48.9%-60.4%)                                         | 77.4% (72.8%-84%)                                             |
| Arizona        | 59.8%                      | 71.8% (61.4%-83.2%)              | 0.83                                             | 90.9% (87.8%-95.8%)                         | 55.2% (51.1%-59.8%)                                         | 81.6% (77.6%-86.6%)                                           |
| Arkansas       | 50.7%                      | 62.7% (51.2%-76.6%)              | 0.81                                             | 84.5% (79.3%-92%)                           | 48.5% (44.3%-53.7%)                                         | 75.1% (70%-82.2%)                                             |
| California     | 68.3%                      | 55.2% (43.5%-70.6%)              | 1.24                                             | 88% (84.6%-94.1%)                           | 51% (46.3%-57.8%)                                           | 79.6% (76.4%-84.8%)                                           |
| Colorado       | 75.8%                      | 57.2% (45.5%-72.2%)              | 1.33                                             | 91% (88.9%-95.9%)                           | 56.9% (51.7%-64%)                                           | 83.3% (80.8%-87.4%)                                           |
| Connecticut    | 77.5%                      | 46.2% (34.9%-62.6%)              | 1.68                                             | 89.4% (87%-94.3%)                           | 51% (46.4%-58.5%)                                           | 81.4% (79.3%-85.1%)                                           |
| Delaware       | 66.3%                      | 56.8% (45.1%-71.9%)              | 1.17                                             | 87.9% (84.4%-93.4%)                         | 51.7% (46.6%-58.6%)                                         | 79% (75.2%-84.6%)                                             |
| District of Columbia | 71.8%         | 47.9% (36.5%-64.1%)              | 1.5                                              | 87.2% (85.2%-93.8%)                         | 48.7% (44.2%-56%)                                           | 78.5% (75.7%-83.6%)                                           |
| Florida        | 68.2%                      | 68.1% (57.2%-80.6%)              | 1                                                | 92.3% (88.6%-96.1%)                         | 60.9% (56.4%-66%)                                           | 83.8% (80.7%-88%)                                             |
| Georgia        | 49.4%                      | 69.6% (58.9%-81.7%)              | 0.71                                             | 87.6% (82.1%-93.6%)                         | 51.8% (47.9%-56%)                                           | 77.9% (73.1%-83.9%)                                           |
| Hawaii         | 78.8%                      | 23% (15.7%-36.7%)                | 3.43                                             | 84.5% (83.3%-89.9%)                         | 41.6% (38.4%-48.1%)                                         | 78% (76.8%-80.9%)                                             |
| Idaho          | 47.9%                      | 65.4% (54.2%-78.6%)              | 0.73                                             | 85.4% (78.9%-92.3%)                         | 52.5% (48%-57.5%)                                           | 76% (70.9%-82.8%)                                             |
| Illinois       | 67.3%                      | 50.1% (38.6%-66.2%)              | 1.34                                             | 86.5% (82.8%-93%)                           | 47.1% (42.6%-54.3%)                                         | 77% (73.8%-82.6%)                                             |
| Indiana        | 53%                        | 51.7% (40.1%-67.6%)              | 1.03                                             | 80.7% (74.8%-89.1%)                         | 42.7% (38.5%-49.2%)                                         | 70.9% (66.3%-78.2%)                                           |
| Iowa           | 58%                        | 52.3% (40.6%-68.1%)              | 1.11                                             | 82.5% (78%-91%)                             | 44.4% (40%-51.1%)                                           | 75.3% (69.4%-80.2%)                                           |
| Kansas         | 58.1%                      | 56.2% (44.5%-71.4%)              | 1.03                                             | 84.4% (79.9%-91.8%)                         | 47.8% (43.2%-54.2%)                                         | 75.4% (70.9%-82.2%)                                           |
| Kentucky       | 53.6%                      | 61% (49.4%-75.3%)                | 0.88                                             | 84.2% (79.3%-92.5%)                         | 49.9% (45.6%-55.5%)                                         | 76% (71.6%-82.7%)                                             |
| Louisiana      | 52.2%                      | 66.4% (55.2%-79.3%)              | 0.79                                             | 86.7% (82.3%-93.6%)                         | 50.5% (46.4%-55.4%)                                         | 76.7% (71.9%-83.1%)                                           |
| Maine          | 73.3%                      | 32.5% (23.1%-48.4%)              | 2.26                                             | 83.8% (81.1%-90.2%)                         | 43.3% (40.3%-51.7%)                                         | 76.5% (74.5%-80.8%)                                           |
| Maryland       | 71.9%                      | 44.4% (33.3%-60.9%)              | 1.62                                             | 86.3% (84%-93.2%)                           | 47.7% (43.2%-55.2%)                                         | 78.1% (75.5%-83.2%)                                           |
| Massachusetts  | 72.7%                      | 48.9% (37.4%-65%)                | 1.49                                             | 88% (85%-93.9%)                             | 49.1% (44.6%-56.4%)                                         | 79.3% (76.8%-83.7%)                                           |
| Michigan       | 55.6%                      | 56% (44.3%-71.3%)                | 0.99                                             | 83.1% (78.4%-91.2%)                         | 45.7% (41.3%-52%)                                           | 73.8% (69.4%-80.7%)                                           |
| State                  | Value 1 (%) | Value 2 (%) | Value 3 (%) | Value 4 (%) | Value 5 (%) |
|-----------------------|-------------|-------------|-------------|-------------|-------------|
| Minnesota             | 61.4%       | 45.2%       | 1.36        | 81.5%       | 43.2%       | 72.6%       |
| Mississippi           | 51.1%       | 67.2%       | 0.76        | 86.6%       | 50.8%       | 76.9%       |
| Missouri              | 51.6%       | 49.1%       | 1.05        | 78.2%       | 41.4%       | 69.3%       |
| Montana               | 54%         | 58.3%       | 0.93        | 83.8%       | 48.8%       | 74.8%       |
| Nebraska              | 52.4%       | 54.5%       | 0.96        | 80.6%       | 45.2%       | 72.1%       |
| Nevada                | 59.6%       | 65.3%       | 0.91        | 88.8%       | 53.7%       | 79.6%       |
| New Hampshire         | 72%         | 33.1%       | 2.17        | 83.4%       | 46%         | 76.1%       |
| New Jersey            | 71.4%       | 55.9%       | 1.28        | 90.4%       | 52.4%       | 80.3%       |
| New Mexico            | 64.1%       | 71%         | 0.9         | 91.6%       | 57.4%       | 83%         |
| New York              | 72.2%       | 57.3%       | 1.26        | 89.5%       | 53.8%       | 81%         |
| North Carolina        | 56%         | 49.7%       | 1.13        | 81.8%       | 43.9%       | 71.8%       |
| North Dakota          | 50.4%       | 64.2%       | 0.79        | 84.8%       | 47%         | 75%         |
| Ohio                  | 53.6%       | 46.9%       | 1.14        | 79.6%       | 40.6%       | 69.2%       |
| Oklahoma              | 55.6%       | 72.2%       | 0.77        | 90.1%       | 57.4%       | 81.6%       |
| Oregon                | 66.7%       | 38.4%       | 1.74        | 82.4%       | 45.5%       | 74.2%       |
| Pennsylvania          | 72.8%       | 49.8%       | 1.46        | 88.2%       | 52.1%       | 80.2%       |
| Rhode Island          | 71.7%       | 59.9%       | 1.2         | 90.5%       | 55.3%       | 81.8%       |
| South Carolina        | 54%         | 60.8%       | 0.89        | 84.8%       | 49.7%       | 75.5%       |
| South Dakota          | 58.7%       | 60.1%       | 0.98        | 86%         | 49.8%       | 76.8%       |
| Tennessee             | 51.7%       | 62.8%       | 0.82        | 85.3%       | 48.3%       | 75.4%       |
| Texas                 | 59.9%       | 65.5%       | 0.91        | 86.7%       | 53%         | 79.5%       |
| Utah                  | 48.1%       | 56.6%       | 0.85        | 80.6%       | 45.3%       | 71.7%       |
| Vermont               | 61.2%       | 30.2%       | 2.02        | 77%         | 37.2%       | 67.8%       |
| Virginia              | 61.4%       | 42.4%       | 1.45        | 81%         | 42.9%       | 72%         |
| Washington            | 67.3%       | 39.7%       | 1.69        | 83%         | 45.5%       | 74.8%       |
| West Virginia         | 25.9%       | 57.4%       | 0.45        | 72.2%       | 37.2%       | 62.9%       |
| Wisconsin             | 60.6%       | 45.9%       | 1.32        | 81.2%       | 42.3%       | 72.5%       |
Wyoming | 49.1% | 68.6% (52.3%-86.3%) | 0.72 | 87% (78.5%-95.4%) | 53.4% (45.3%-63.5%) | 77.8% (70%-88%)

*Received at least one COVID-19 vaccine dose

**Figure 1:** Estimated percentage *immunologically exposed* on October 31, 2021, for each US county and state.

Footnote: The background coloring indicates the state-specific distribution of immunity as a function of infections and vaccinations. Black dots represent counties in a state, red dots the state average. The orange diamond represents the state-population-weighted national averages of the percentage ever infected and vaccinated (this does not represent the national average of immunity because the calculation for immunity is state-specific).

**Figure 2:** State-level estimates and uncertainty intervals of the percentage *immunologically exposed, effectively protected* against infection, and *effectively protected* against severe disease over time.

**Figure 3:** County-level estimates of the fraction of the population *effectively protected* against infection at four time-points between January 31, 2021 and October 31, 2021.

**Figure 4:** Relative contribution of prior infection and vaccination to population immunity for each county at four time-points between January 31, 2021 and October 31, 2021.

Footnote: The percentage ever infected and the percentage vaccinated are categorized with cut-off scores of 40%, 50% and 60%. These values which roughly corresponds to the quantile breakpoints of the estimates of ever infected and vaccinated on October 31, 2021.
