**Evaluation of an equity-focused vaccine allocation policy on vaccination rates and COVID-19 outcomes in California, 2021**

COVID-19, Equity, Vaccination, Evaluation

### Abstract (171 words):

In March 2021, California implemented a vaccine equity policy that prioritized COVID-19 vaccine allocation to communities identified as least advantaged by an area-based socioeconomic measure, the Healthy Places Index (HPI). We conducted quasi-experimental and counterfactual analyses to estimate the effect of this policy on COVID-19 vaccination, case, hospitalization, and death rates. Among prioritized communities, vaccination rates increased 28.4% (95%CI: 22.1% - 35.1%) following policy implementation. Furthermore, an estimated 160,892 (95%CI: 108,878 – 221,815) COVID-19 cases, 10,248 (95%CI: 6,111 – 14,853) hospitalizations, and 679 (95%CI: -32 – 1,451) deaths in the least advantaged communities were averted by the policy. Despite these improvements, the share of COVID-19 cases, hospitalizations, and deaths in prioritized communities remained elevated. These estimates were robust in sensitivity analyses that tested exchangeability between prioritized communities and those not prioritized by the policy, model specifications, and potential temporal confounders including prior infections. Correcting for disparities by strategically allocating limited resources to the least advantaged or most impacted communities can reduce the impacts of COVID-19 and other diseases, but may not eliminate health disparities.

### Background

Since the SARS-CoV-2 virus emerged in 2020, the COVID-19 pandemic has exacerbated and further unveiled longstanding health disparities in California, the United States, and the world (1–4). While these disparities are partially explained by differential rates of comorbidities and other medical risks including age, social and structural determinants also play a key role (5,6). These social and structural factors led to disparities in access to testing, healthcare, the opportunity to work remotely, the ability to isolate or quarantine, and other essential components of pandemic response strategies including vaccine and treatment access (5,7,8). Equity-focused policies that deliberately allocate more resources to communities most impacted by these inequities offer a promising strategy to mitigate health disparities.

Vaccination strategies may be particularly amenable to equity-focused policies due to their long-lasting protective effects. The high efficacy of COVID-19 vaccines and their ability to induce durable protection against severe outcomes such as hospitalization and death make COVID-19 vaccines a valuable medical countermeasure to combat disparities (9). However, equitable vaccination is unlikely to be achieved without explicit effort to account for disparate access and uptake to vaccines (10). Instead, vaccination policies that prioritize the least advantaged or most impacted populations are required to equitably distribute the benefits of vaccination (11).

To reduce inequities in COVID-19 burden and prevent inequities in vaccination among its diverse residents, the State of California implemented an equity-focused policy early during vaccination rollout. This vaccine equity allocation policy—hereafter “the policy”—implemented in March 2021 distributed 40% of available COVID-19 vaccines to the least advantaged quarter of communities in California (12). The policy utilized the Healthy Places Index (HPI), an area-based socioeconomic measure specific to California that provides an assessment of the ability of community residents to live a healthy life (13). The HPI facilitated identification of COVID-19-related disparities in California and formed the basis of other equity-focused policies in California during the pandemic, including The Blueprint for a Safer Economy which was in effect from August 2020 through June 2021 (14). While making up 27% of the state’s population, individuals residing in ZIP codes classified as least advantaged by falling in the lowest 25% of HPI index scores experienced almost 40% of all COVID-19 cases and deaths, motivating the allocation of 40% of vaccines to these communities (12).

The primary objective of this analysis is to evaluate the impact of California’s vaccine equity allocation policy on COVID-19 vaccination rates and outcomes. We used a quasi-experimental difference-in-differences approach to estimate the effect of the policy on vaccination rates in communities that received the equity allocation. We then used a counterfactual approach to estimate the number of COVID-19 cases, hospitalizations, and deaths averted due to the policy.

#### Data Used

The HPI is an area-based socioeconomic measure developed by the Public Health Alliance of Southern California (PHASC) that integrates data from the American Community Survey, California Environmental Protection Agency, Bureau of Labor Statistics, and other agencies to generate an index score calibrated to life expectancy at birth. Details of HPI development are available in PHASC’s technical report (15). Since some areas were not assigned scores because of small population or other exclusion criteria, the Vaccine Equity Metric (VEM) was derived by the California Department of Public Health (CDPH) in March 2021 to ensure that all ZIP codes in the state could be counted towards vaccine allocation. The VEM combined scores from HPI version 2.0 with CDPH-derived ZIP code scores (13,16). CDPH assigned a VEM score for every ZIP code in California by creating a predictive regression model trained on existing HPI scores given known data points from the American Community Survey, Surgo Venture’s COVID Community Vulnerability Index (17), and the California “Hard-to-Count” Index (18). These scores were percentile ranked and partitioned into quartiles using quartile thresholds from the HPI to determine VEM Q1 ZIP codes prioritized by the policy. Thus, the first quartile or VEM Q1 was interpreted as the 25% of ZIP codes in the state where residents have the least opportunity to live a healthy life. The policy then allocated 40% of available vaccines to VEM Q1 communities with the remaining 60% of vaccines divided evenly among VEM Q2, Q3, and Q4 communities. The policy also included equity-oriented technical assistance, contracting support, staffing resources, and mobile vaccination sites for Local Health Jurisdictions (LHJs) to aid their vaccination outreach (12).

COVID-19 vaccination records were collected from statewide immunization databases in California. The date and ZIP code of COVID-19 vaccinations administered, regardless of dose number, were joined with ZIP-level VEM scores to generate a dataset of daily vaccinations administered by VEM quartile.

Person-level records of confirmed SARS-CoV-2 infection in California were used to derive weekly time series of COVID-19 cases, hospitalizations, and deaths. Individual addresses reported in the CDPH Electronic Lab Reporting system were used to assign each individual’s ZIP code of residence. Cases were defined as individuals with a lab-confirmed, positive SARS-CoV-2 Nucleic Acid Amplification Test (NAAT) test reported to CDPH regardless of symptom status. Hospitalizations were determined from the California COVID-19 Reporting System and supplementary hospitalization reports. COVID-19 deaths were defined as individuals with confirmed COVID-19-associated death reported to CDPH by local health departments. COVID-19 confirmed cases and deaths follow CDPH guidance and definitions set by the Council of State and Territorial Epidemiologists (CSTE) (19). Population data were drawn from 2020 5-year American Community Survey (ACS) estimates.

#### Analytic Approach

***Vaccination Outcomes***

We conducted a difference-in-differences (DiD) analysis to compare the rate of vaccination in prioritized VEM Q1 ZIP codes to non-VEM Q1 ZIP codes before and after the policy was implemented. A Poisson generalized linear model (GLM) was fitted with the number of vaccines administered by ZIP code as the outcome and ZIP code population as an offset term. Main effects for binary before/after policy implementation, binary VEM Q1/non-Q1 status, and their interaction were included along with a main effect on county to account for variability between LHJs. Symmetric four-week periods before and after the policy was implemented on March 1, 2021 were used to estimate the immediate effect of the policy on vaccination rates before vaccines became more widely available in May 2021. The interaction term—operative in after-policy periods in VEM Q1 ZIP codes—was the target parameter, representing the change in vaccination rate in VEM Q1 ZIP codes compared to non-VEM Q1 ZIP codes, ostensibly due to the policy. Robust standard errors using the sandwich estimator were used for all regression models to generate 95% confidence intervals around effect estimates.

We conducted additional analyses to probe key assumptions of the DiD model, including the potential effect of secular decline in vaccination rates due to depletion of the eligible population, the suitability of non-VEM Q1 populations to serve as controls for VEM Q1 populations, and the potential for unmeasured confounders (Supplementary Material).

First, vaccination rates may be expected to decline over time due to depletion of the population of unvaccinated individuals. This could bias DiD results, particularly if there were differential vaccination rates across VEM areas. To account for this, an additional model was fitted with a main term for the proportion of the population unvaccinated. Second, non-VEM Q1 ZIP codes may not serve as a valid comparison group for VEM Q1 ZIP codes since they differ by VEM score and the VEM constituent indicators. To assuage concerns with this potential for non-exchangeability, the same DiD model was rerun, but restricted to ZIP codes that fall in the second or third octile of all VEM scores (upper half of VEM Q1 or lower half of VEM Q2, respectively). This analysis sacrifices sample size for a potentially less-biased comparison group, assuming that ZIP codes falling on either side of the 25th percentile cutoff used to define VEM quartiles are more similar. In this analysis, octile 3 ZIP codes that did not receive the equity allocation serve as the control for octile 2 ZIP codes that did receive the equity allocation. Finally, a negative controls analysis was conducted by refitting the DiD model for all pairwise combinations of VEM quartiles, with the lower VEM quartile in each instance serving as the intervention group. This analysis sought to test for the presence of unmeasured confounders that could bias DiD results and would be identified by significant DiD estimates among non-VEM Q1 ZIP codes.

#### *COVID-19 outcomes*

We utilized a counterfactual approach in which the expected number of COVID-19 cases, hospitalizations, and deaths in the absence of the policy were estimated from fitted generalized linear models (GLMs) and compared to observed outcomes (20). All COVID-19 case, hospitalization, and death data were aggregated at the ZIP code-week level, with weeks defined by the preceding Monday of each record to align with the Monday, March 1, 2021 policy start date. The observation period was defined as December 14, 2020—when Phase 1A of California’s vaccination campaign began (21)—through November 1, 2021—just prior to the emergence of the Omicron variant and widespread booster rollout.

To prevent overfitting and avoid reliance on a single parametric model, several candidate Poisson GLMs were fitted with COVID-19 cases, hospitalizations, and deaths as outcomes. All models included an offset for ZIP code population, county and VEM quartile main effects, cubic spline bases with knots every three weeks, and a binary intervention variable for whether the ZIP-week observation was in a VEM Q1 ZIP code and took place after March 1, 2021 coinciding with the beginning of the intervention. Additional candidate linear predictors included cumulative case rate, cumulative vaccinations administered rate, test rate, population over age 50 years, and interaction terms (Supplementary Tables 2-4). Candidate models were compared via 10 rounds of 10-fold cross validation and performance was assessed via estimation of the mean squared error (MSE) in out-of-sample predictions following policy implementation. The square root of the MSE gives a more interpretable measure of model fit: the average error in outcomes estimated per ZIP-week observation. ZIP codes in counties with less than 100K population—together just 2.4% of California’s population—were excluded in this model evaluation step to avoid errors in the cross-validation procedure caused by counties containing insufficient ZIP codes to allocate to both training and validation sets.

For each outcome, the model with the lowest MSE was used to generate counterfactual estimates for VEM Q1 in the absence of the policy by setting the intervention variable (and any interaction terms with the intervention variable) to 0 and re-estimating the outcome from the fitted model. Averted COVID-19 cases, hospitalizations, and deaths in VEM Q1 were estimated as the difference between these counterfactual model predictions and observed values. Clustered nonparametric bootstrapping at the ZIP code level with 10,000 bootstrapped samples was conducted to generate estimates of uncertainty in outcomes avoided that are robust to model misspecification. To ensure that outcomes averted results were not driven solely by the best performing model, estimates were also generated from the next best performing models, as described in the supplementary material.

#### Code and data availability

Where possible, data and code used in these analyses is available on the California Open Data Portal ([data.ca.gov](https://data.ca.gov)) and on GitHub (<https://github.com/cmhoove14/VaxEquityEval>). However, ZIP-level weekly time series of COVID-19 outcomes are considered protected public health data. Investigators interested in obtaining these data should contact the corresponding author to discuss the process for developing a data-use agreement and obtaining the data. All analyses were conducted using R Statistical Software (4.04, (22)) utilizing the tidyverse (23), splines, lme4 (24), sandwich (25), and fastglm packages

### Results

#### Policy impact on vaccinations administered

Nearly 14.9 million COVID-19 vaccines were administered in California in the combined 4-week periods before and after the policy began on March 1, 2021 (February 1, 2021 - March 29, 2021). The vaccination rate per 100,000 in the 8-week period was highest in VEM Q4 and lowest in VEM Q1 (Exhibit 1). However, the vaccination rate increased the most in VEM Q1 following the equity allocation, from 9,998 vaccinations/100,000 in the four weeks before the equity allocation to 18,146 vaccinations/100,000 in the four weeks after (Exhibit 1).

The vaccination rate in VEM Q1 ZIP codes in the four weeks following policy implementation increased by an estimated 28.4% (95%CI: 22.1% - 35.1%) compared to non-VEM Q1 ZIP codes. Adjusting for the proportion of the population unvaccinated led to an insignificant change in the effect estimate to 26.9% (95%CI: 20.9% - 33.1%). Pairwise comparisons among all VEM quartiles in the negative controls analysis suggest there were also significant relative increases in the vaccination rate among VEM Q2 ZIP codes compared to VEM Q3 and Q4 ZIP codes (increases of 8.0% (2.4% - 13.8%) and 10.3% (5.0 % - 15.7%), respectively) in the after-policy period (Supplementary Table S1). Finally, restricting the analysis to ZIP codes in the second or third VEM octiles for better exchangeability between treated and untreated groups led to an estimated 8.9% (95%CI: 1.1% - 17.2%) increase in vaccination rate in VEM octile 2 communities.

#### Policy impact on COVID-19 outcomes

The best performing cases model included a post-intervention spline term as well as the cumulative vaccination rate (Supplementary Table 2). Out-of-sample error from this model was relatively low, translating to approximately 17 cases per ZIP-week observation, and the model closely reproduced observed outcomes (Supplementary Figure 1), providing confidence in counterfactual estimates used to estimate outcomes averted.

From this model, it was estimated that in the eight months following the policy, 160,892 (95%CI: 108,878 – 221,815) cases were averted in VEM Q1 ZIP codes. This represents 30.3% of all expected cases that would have occurred in VEM Q1 between March 1 and November 1, 2021 in the absence of the policy. Most of the cases averted in this time period came after July 1, 2021, during the beginning of California’s Delta variant wave (Exhibit 2). However, 22,875 (95%CI: 16,067 – 30,582) cases were averted in the first two months following the equity allocation.

While 27% of California’s population resides in VEM Q1 areas, residents in VEM Q1 accounted for 37% of cases in the two months before the policy was implemented (Exhibit 3). Excess COVID-19 cases among the least advantaged VEM Q1 communities prioritized by the policy were reduced in the post-policy period (Exhibit 3, blue line), while counterfactual estimates suggest that disparities would have persisted unabated without the policy (Exhibit 3, orange line). In fact, in April and again in July 2021, the proportion of overall cases occurring in VEM Q1 matched the proportion of the state population residing in VEM Q1, suggesting that the burden of disease in these communities was briefly not disproportionate (Exhibit 3, blue line overlapping horizontal dashed lines).

Results from the same analyses estimating the impact of the policy on COVID-19 hospitalizations and deaths are reported in detail in the supplementary material. In brief, 10,248 (95%CI: 6,111 – 14,853) hospitalizations and 679 (95%CI: -32 – 1,451) deaths were estimated to be averted due to the policy.

### Discussion

Equity-based policies to guide public health programs and resource allocation are critical to addressing health disparities. The effectiveness of these policies, however, often lacks rigorous evaluation. Throughout the COVID-19 pandemic, the CDPH sed area-based socioeconomic measures such as the VEM to aid equity-based policies. In this analysis, we demonstrate that one such policy to distribute more vaccines to less advantaged communities led to increased vaccination rates and subsequent decreases in COVID-19 cases, hospitalizations, and deaths among the prioritized populations. Specifically, we estimate that vaccination rates increased 28.4%, and more than 160,000 cases, 10,000 hospitalizations, and 670 mortalities were averted because of the policy.

Our estimate of a 28.4% increase in the vaccination rate in VEM Q1 areas in the four weeks following the policy compared to all other areas varied in sensitivity analyses that tested key assumptions of the base model. When compared only to VEM Q2 areas, we estimate a 20.7% increase, while comparing only the upper half of VEM Q1 to the lower half of VEM Q2 results in a further attenuated estimate of an 8.9% increase. While our negative controls analysis suggests there were significant increases in vaccination rates in both VEM Q2 and Q3 communities compared to those in Q4, adjustment for the proportion of the population that was vaccinated before and after the policy was implemented had very little effect on these estimates. Together, these results may suggest the presence of additional factors that influenced vaccination rates at the time the policy was implemented. Another potential explanation is that VEM Q1 and Q2 ZIPS often border each other, leading to potential for spillover effects of the policy into VEM Q2 ZIPS. Regardless, the equity allocation appears to have led to at least an 8.9% increase in the vaccination rate among intended VEM Q1 residents.

The increased vaccination rate among VEM Q1 communities also resulted in significant decreases in COVID-19 outcomes. Over the eight months after the policy, more than 160,000 cases, 10,000 hospitalizations, and 670 deaths were averted among VEM Q1 residents. These results corroborate prior theoretical work that found vaccine distribution to disadvantaged communities can reduce inequities in COVID-19 outcomes (11). Our results are also in agreement with previous analyses that quantified the impact of vaccinations on COVID-19 outcomes among all Californians over a similar period. Tan et al. found that approximately 1.5 million cases, 73,000 hospitalizations, and 20,000 deaths were averted due to all vaccinations in California through mid-October of 2021 (28). Our results—evaluated from the beginning of the policy in March 2021 through the end of October 2021—suggest that the policy accounted for 10.5% of these averted cases, 14.1% of averted hospitalizations, and 3.5% of averted mortalities.

Our analysis has the added value of assessing how equitably these averted outcomes were distributed across the population. COVID-19 heavily impacted VEM Q1 communities in the pre-vaccine era of the pandemic, with these communities accounting for 40% of all cases and deaths, despite making up only 27% of California’s population (12). Our counterfactual estimates imply that this disparity would have persisted at similar levels without the policy. However, the observed proportion of cases occurring in VEM Q1 communities was briefly equivalent to the proportion of the population in these communities following the policy. This implies that the policy reduced inequities in the distribution of COVID-19 cases but did not successfully eliminate these inequities entirely.

The majority of estimated COVID-19 outcomes averted in this analysis were accumulated in the Delta wave in July and August 2021, more than four months after the policy was implemented in early March. Attributing COVID-19 outcomes averted in this period to the policy may be tenuous since individuals vaccinated earlier because of the policy may feasibly have been vaccinated by August 2021 despite the policy. However, some individuals who were vaccinated because of the policy may otherwise never have been vaccinated due to increased politicization of the vaccine in summer 2021 (29) or other factors such as lack of access. Estimating the size of these and other relevant population subsets that were affected by the policy is infeasible. Despite the large effect estimated in the Delta wave, significant estimates of cases, hospitalizations, and deaths averted were attained quickly after the equity allocation was implemented, well before the Delta wave in California.

The estimate of cumulative deaths averted due to the policy failed to reach significance (i.e. overlapped with 0 mortalities averted) at the end of the estimation period, though estimates were significant in some weeks prior to the Delta period. Temporal trends of deaths averted in the eight months following the policy also do not align as well with cases and hospitalizations, suggesting that different factors may have influenced the progression of COVID-19 cases and hospitalizations to deaths. The Delta variant’s increased severity, particularly among unvaccinated individuals (30), is likely partially responsible for this. In addition, changing clinical treatment aided by the approval of remdesivir (31) and monoclonal antibodies (32) over the course of 2021 could confound the effect of the intervention variable and influence the counterfactual mortality estimates. Similarly, survivorship bias could affect accurate estimation of deaths in the post-policy era as many individuals that were vulnerable to severe COVID-19 outcomes may have succumbed to the disease prior to the widespread availability of vaccines (33).

There are inherent limitations in a complex policy analysis assessing the impact of vaccination policies. Our main challenge was overcoming the lack of a consistently reliable comparison group for VEM Q1 communities that were prioritized by the policy. We attempted to resolve this issue via sensitivity analyses that compared the upper half of VEM Q1 (second VEM octile) with the lower half of VEM Q2 (third VEM octile) on the assumption that these areas are arbitrarily divided by the quartile cutoff, but are quite exchangeable in reality. We still found significant, albeit attenuated, increases in the vaccination rate in the second VEM octile after the policy was implemented.

Analyzing the effect of an upstream vaccination policy on COVID-19 outcomes is more challenging than evaluating the effect of the policy on vaccinations. Multi-dose vaccination schedules along with variability in exposure, testing access, and underlying health conditions may all affect observed rates of COVID-19 outcomes. The counterfactual approach we used to estimate outcomes averted due to the policy has been used previously to estimate the impact of vaccination campaigns in which a control group does not exist (20). This approach to generate counterfactual estimates in the absence of the policy is similar to a synthetic control analysis in which counterfactual estimates are generated for the target area or population using data from related, but non-targeted areas or populations and compared to what was actually observed.

Our approach to evaluate candidate models on their out-of-sample performance optimizes our counterfactual estimates by rigorously identifying the model with the best out-of-sample predictions. The models with the best performance for each outcome in this analysis included terms related to important drivers of COVID-19 outcomes including older age, prior vaccination, and prior infections that reduce population susceptibility. Out-of-sample error from these models was relatively low across all outcomes considered, and bootstrapped resampling at the ZIP code level to generate uncertainty estimates also ensures that our results are not reliant on a small number of overly influential observations (such as very high population ZIP codes) and that results accurately reflect uncertainty in the estimation procedure. Finally, we also estimated the main outcomes averted measure for the next nine best performing models to ensure that our results were not entirely reliant on the best performing model and found similar results across cases, hospitalizations, and deaths.

In conclusion, we found consistent evidence that California’s vaccine equity allocation policy that distributed more vaccines to the least advantaged and most impacted communities resulted in substantial increases in vaccination rates and reductions in COVID-19 outcomes. However, the policy was not sufficient to eliminate disparities in vaccination rates and COVID-19 risk experienced by these communities. Additional public health interventions that address disparities across all social determinants of health, in addition to outcome-specific policies such as the vaccine equity allocation, are needed to achieve health equity (34).

### Exhibits

**EXHIBIT 1: Vaccination rates increased more in prioritized VEM Q1 communities after the policy (table)**

Caption: Vaccinations administered by Vaccine Equity Metric (VEM) quartile in the four-week periods before and after the policy was implemented on March 1, 2021. Absolute numbers are shown along with rates per 100,000 residents in parentheses.

Source/Notes: Authors analysis of Feb 1, 2021 – March 29, 2021 vaccination data.

**EXHIBIT 2: COVID-19 cases averted after policy implementation (figure)**

Caption: Time series of weekly cases stratified by vaccine equity metric (VEM) quartile in California from March 1, 2021 – November 1, 2021. Cases remained at relatively low levels around the time the policy was implemented on March 1, 2021 until the delta variant caused increased activity beginning in July 2021. Hatched blue areas indicate cases that were averted in VEM Q1 as estimated in the counterfactual analyses. Significant estimates of cases averted were reached soon after the policy was implemented, though the majority of outcomes averted came during the delta wave when COVID-19 activity was significantly higher.

Source/Notes: Authors analysis of COVID-19 case data collected from December 2020 – November 2021

**EXHIBIT 3: Disproportionate burden of COVID-19 cases in VEM Q1 (figure)**

Caption: The percent of all COVID-19 cases occurring among residents of the least advantaged quartile of the vaccine equity metric (VEM Q1). The blue and orange lines show, respectively, the observed and counterfactual estimates of the percent of cases occurring among VEM Q1 populations. The vertical dashed line indicates the week the policy was implemented, and the horizontal dashed line indicates the percent of California’s overall population residing in VEM Q1 ZIP codes. This population percent serves as a reference for the percent of cases that would occur in VEM Q1 if cases were equally distributed across VEM quartiles. Observations above this line suggest that COVID-19 cases were occurring disproportionately among VEM Q1 populations. The blue line falling closer to the horizontal reference line in the after-policy period suggests that the policy reduced disparities in COVID-19 cases among VEM Q1 residents.

Source/Notes: Authors analysis of COVID-19 case data collected from December 2020 – November 2021

**Exhibit 1**:

|  |  | Vaccines administered (per 100,000) | |
| --- | --- | --- | --- |
| VEM Quartile | Population | Before | After |
| 1 | 10,617,434 | 1,061,509 (9,998) | 1,926,615 (18,146) |
| 2 | 9,902,750 | 1,386,711 (14,003) | 2,085,838 (21,063) |
| 3 | 9,397,006 | 1,641,233 (17,465) | 2,285,986 (24,327) |
| 4 | 9,298,697 | 1,898,517 (20,417) | 2,589,952 (27,853) |

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