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Neighborhood-level COVID vaccination and booster disparities: A population-level analysis across California

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ABSTRACT

Objectives: To describe vaccine and booster uptake by neighborhood-level factors in California.
Methods: We examined trends in COVID-19 vaccination up to September 21, 2021, and boosters up to March 29, 2022 using data from the California Department of Public Health. Quasi-Poisson regression was used to model the association between neighborhood-level factors and fully vaccinated and boosted among ZIP codes. Sub-analyses on booster rates were compared among the 10 census regions.
Results: In a minimally adjusted model, a higher proportion of Black residents was associated with lower vaccination (HR = 0.97; 95%CI: 0.96–0.98). However, in a fully adjusted model, proportion of Black, Hispanic/Latinx, and Asian residents were associated with higher vaccination rates (HR = 1.02; 95%CI: 1.01–1.03 for all). The strongest predictor of low vaccine coverage was disability (HR = 0.89; 95%CI: 0.86–0.91). Similar trends persisted for booster doses. Factors associated with booster coverage varied by region.
Conclusions: Examining neighborhood-level factors associated with COVID-19 vaccination and booster rates uncovered significant variation within the large and geographically and demographically diverse state of California. Equity-based approaches to vaccination must ensure a robust consideration of multiple social determinants of health.

1. Introduction

The COVID-19 pandemic has disproportionally impacted the morbidity and mortality of marginalized communities in the United States, including racial and ethnic minority groups (Stokes et al., 2020), rural communities (Centers for Disease Control and Prevention, 2022), and people living in poverty (Jung et al., 2021). To date, COVID-19 vaccination and booster coverage is also lower among these same populations (Barry et al., 2021; Diesel et al., 2021; Fast et al., 2021; Hughes et al., 2021; Williams et al., 2022), as well as among younger people and those with limited access to the internet (Diesel et al., 2021; Whiteman et al., 2021). Much of the conversation surrounding COVID-19 vaccination disparities has centered around "vaccine hesitancy" and individual-level barriers to vaccinations. However, there are structural barriers to vaccination uptake influenced by multiple intersecting social determinants of health (SDOH), including structural racism (Bailey et al., 2017; Egede & Walker, 2020; Johnson, 2020; O'Brien et al., 2020), which deserve attention as we evaluate the equity of vaccination efforts (Largent et al., 2021). Deeper understanding of place-based determinants of health is core to improving public health interventions that target entire communities to improve the health of populations, which can be used in combination with individual-level behavioral or clinical interventions to advance pandemic response and preparedness.

Previous literature examining place-based disparities in COVID-19

Abbreviations: ACS, American Community Survey; CDPH, California Department of Public Health; COVID-19, Coronavirus Disease 2019; LEP, Limited English Proficiency; SDOH, Social Determinants of Health; UCSF, University of California, San Francisco; VEM, Vaccine Equity Metric; ZCTA, Zip Code Tabulation Area.

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vaccination rates in the U.S. has used national or statewide datasets and examined differences at the county level (Barry et al., 2021; Hughes et al., 2021; Saelee et al., 2022). However, it is well known that place-based influences on health behaviors are often more localized than at the county level, with more geographically granular neighborhood-level drivers emerging as strong determinants of health-seeking behaviors. Multiple phenomena that influence health outcomes, such as structural racism, social networks, or public health promotion, exist on different spatial scales (Brown & Homan, 2022; Cummins et al., 2007). Therefore, we explored neighborhood-level factors stratified by region to gain a deeper understanding of how region and neighborhood influence COVID-19 vaccination and boosters.

Finally, most of the current research on disparities in COVID-19 vaccination limits the scope to "fully vaccinated" with a primary vaccine series; however, there is significant evidence that receiving a booster dose is associated with protection against COVID-19 infection and subsequent hospitalization (Danza, Koo, & Haddix, 2022; Kuehn, 2022). Taken together, the need to examine local, neighborhood-level determinants of COVID-19 vaccination rates for both primary series and booster doses is critical for understanding equitable access to health interventions over the course of a public health emergency.

California's response to the pandemic and COVID-19 vaccination rollout is particularly relevant for our understanding of place-based disparities in public health interventions, given the geographic diversity and size of the population that this state represents. Early on in the pandemic response, California introduced multiple initiatives to identify and direct resources, including equitable vaccine distribution, toward communities disproportionally affected by the COVID-19 pandemic (California Department of Public Health, 2022). ZIP codes were assigned to Vaccine Equity Metric (VEM) quartiles based on the California Healthy Places Index combined with California Department of Public Health (CDPH) derived scores to measure healthy community conditions (California Department of Public Health, 2021a). In the first months of rollout, vaccine coverage was fairly consistent across all VEM quartiles, but over time vaccination rates grew higher in zip codes labeled as "more healthy." As California residents became eligible for boosters, the difference in the least healthy to most healthy VEM quartile persisted (California Department of Public Health, 2021a). These disparities suggest that efforts to increase equity in vaccine delivery in California may have waned over time and underscored the importance of teasing apart specific drivers of COVID-19 vaccination vs. booster dose completion rates. In this study, we conduct a more granular examination of disparities, furthering these important previous VEM analyses by examining place-based variables independently. We use ZIP code level data to approximate neighborhood (Chen & Krieger, 2021; Nagasako et al., 2018), to examine how demographics and other neighborhood-level factors are associated with vaccination and booster rates both among ZIP codes across California and within 10 different regions of the state.

2. Material and Methods

2.1. Study sample

We used population-level data for the entire state of California, including multiple publicly available data sources to generate a comprehensive view of SDOH and COVID-19 vaccination and boosters. Our analyses utilized data from zip code tabulation areas (ZCTAs), the finest level of geographic granularity for which COVID-19 vaccination data was available. The average population per ZIP code is estimated to be about 8,000, but can vary widely by location. Because ZIP codes designate postal routes, the U.S. Census Bureau created ZCTAs to approximate areas covered by ZIP codes. We limited our estimated total population to those aged 12 and older, as vaccines and boosters were not approved for younger residents during the study period. Population counts were calculated by CDPH from the 2015–2019 American Community Survey (ACS) by taking proportionate counts from ACS age ranges.

2.2. Primary outcomes: COVID-19 vaccination and booster rates

ZCTA data on vaccinations, boosters, and population counts were obtained from the California Health and Human Services Open Data Portal and were based on 2010 ZCTA census designations. Persons fully vaccinated between January 5 and September 21, 2021 were defined as those with 2 Pfizer/Moderna doses or 1 dose of Johnson & Johnson vaccine. Proportion fully vaccinated was defined as the number of persons fully vaccinated divided by the total population aged $\geq$12 years. Booster doses are reported separately within the Open Data Portal, defined as an additional dose of any vaccine type after the primary vaccination series was completed. All booster doses up through March 29, 2022 were included in the analysis. Proportion boosted is defined as the number of booster doses divided by the total population aged $\geq$12 years. Proportion boosted among eligible is defined as number of booster doses divided by the number fully vaccinated.

2.3. Predictor variables at the neighborhood-level

We used a theoretical model to map out how different factors might influence vaccination status and then selected variables for our analysis based on this model with adjustments for collinearity and data availability. Our variable selection of place-based determinants of COVID-19 vaccination and booster rates was driven by the Healthy People, 2020 SDOH framework (Nagasako et al., 2018). We selected variables that represented all 5 domains within this framework: economic stability (low income), education (not high school graduate), neighborhood and built environment (population density, no internet access), social and community context (race, ethnicity, sex, age, limited English proficiency, foreign born), and health/healthcare (uninsured, disability).

The ACS (2015–2019) estimates at the ZCTA level included race, ethnicity, age, sex, education, uninsured, limited English proficiency (LEP), foreign born, broadband internet access, population density, and disability. Race and ethnicity were categorized as non-Hispanic White, Black, Hispanic/Latinx, and Asian (all Asian ethnicities not including Native Hawaiians or Pacific Islanders) and included residents reporting a single or multiple race or ethnicities.

We also used the Department of Housing and Urban Development (HUD)'s data to create an extremely low-income measure (<30% median income). Interactive maps of vaccination and neighborhood variables can be found in the UCSF Health Atlas: healthatlas.ucsf.edu (UCSF Health Atlas, 2022).

We mapped the data using the 2019 ZCTA shapefile from NHGIS (Manson SS et al., 2022).

2.4. California regions

California Census Regions were used for regional analysis. These 10 regions are geographically contiguous groupings of counties created by the California Complete Count Office. Groupings are based on their hard-to-count populations, like-mindedness of the counties, capacity of community-based organizations within the counties, and state Census staff workload capabilities (California Census, 2020).

3. Theory/calculation

3.1. Statistical analyses

We completed analyses for the entire state of California and used the 10 California Census Regions for regional analysis. We focused on unadjusted and adjusted estimates for both primary outcomes: 1) cumulative number of fully vaccinated individuals, and 2) cumulative number of boosters. First, we descriptively summarized the outcomes, as well as reported the ZCTA-level characteristics to collectively examine the distribution of vaccination and booster rates by a composite neighborhood SDOH indicator. Pearson correlations were used to identify highly correlated predictor variables (≥0.70).

Finally, we ran adjusted quasi-Poisson generalized linear regression models, omitting highly collinear variables from the model. All variables reported as a proportion were divided by 10, and population density was divided by 10,000, so estimated effects were per 10% and 10,000-unit increase, respectively. Ultimately non-Hispanic White race and foreign born were omitted from the analysis due to collinearity with other key variables. Quasi-Poisson models with ZCTA level observations were offset for the natural logarithm of population age ≥12 years and adjusted for county. Because the data were over-dispersed, we used a quasi-likelihood approach. We also considered negative binomial models but found quasi-Poisson models performed better in terms of goodness-of-fit. For both vaccination and booster models, a minimally adjusted model including race, ethnicity, sex, and age ≥65 variables was compared to a fully adjusted model. Descriptive analysis and models for boosters were also built for each of the 10 Census Regions for comparison. We opted to narrow our scope for the regional analysis on boosters as this was a priority of local public health officials at the time of analysis.

Quasi-Poisson models were built in SAS version 9.4. Visualizations and data preparation were completed in R (version 4.0.3) RStudio (version April 1, 1106) and ArcGIS Pro 2.9.2.

4. Results

CDPH reported full vaccination coverage on 33,307,335 individuals ≥12 years old, 22,781,179 of whom were fully vaccinated as of September 21, 2021. CDPH reported booster coverage on 33,295,738 individuals ≥12 years old, 14,295,327 of whom were boosted as of March 29, 2022. The median vaccination coverage was 66.1% (among 1649 ZCTAs with recorded vaccination data). The median booster coverage was 39.1% (among 1634 ZCTAs with recorded booster data).

4.1. Regression models

In the minimally adjusted model for full vaccination (Fig. 1a, Model 1), a 10% increase in Black and male residents was associated with decreases in vaccination coverage of 2.7% and 7.0% respectively, while a 10% increase in Asian residents and those ≥65 years old was associated with increases in vaccination of 3.6% and 4.7% respectively. In the fully adjusted model for full vaccination (Fig. 1a, Model 2), all race and ethnicity variables (i.e., proportion Asian, Black, and Hispanic/Latinx residents) were associated with higher rates of vaccination. Also in the fully adjusted model, an increase in proportion of residents who were male, extremely low income, less educated, without broadband internet, uninsured, or disabled was associated with lower vaccination coverage, while increased proportion of residents age ≥65 or LEP were associated with higher vaccination coverage. Population density was not significantly associated with any decrease or increase in vaccination coverage.

In the minimally adjusted model for boosters (Fig. 1b, Model 1), a 10% increase in Black, Hispanic, and male residents was associated with decreases in booster coverage of 4.4%, 3.6%, and 7.8% respectively, while a 10% increase in Asian residents and those ≥65 years old was associated with increases in vaccination of 4.5% and 7.1% respectively. In the fully adjusted model for boosters (Fig. 1b, Model 2), all race and ethnicity variables (i.e., proportion Asian, Black, and Hispanic/Latinx residents) were associated with higher rates of vaccination. Similar to the fully adjusted models for full vaccination, an increase in proportion of residents who were male, extremely low income, less educated, without broadband internet, uninsured, or disabled was associated with lower booster coverage. Increased proportion of residents age ≥65 or LEP were associated with higher vaccination coverage. In contrast to models for full vaccination, population density was associated with higher booster coverage with a 10,000 person per km increase in population density associated with a 8.4% increase in booster coverage.

4.2. Regional analysis

Regional data show a wide range of full vaccination in California by region with 53.6% in Southern San Joaquin Valley to 84.4% in the San Francisco Bay Area through September 21, 2021 (Tables 1a-1b, Fig. 2a). Booster coverage in California ranged from 27.2% in Southern San Joaquin Valley to 64.2% in the San Francisco Bay Area (Tables 1a-1b, Fig. 2b). Among the fully vaccinated, median booster coverage ranged from 40.5% in San Diego-Imperial to 65.9% in the San Francisco Bay Area (Tables 1a-1b).

Fully adjusted models by region show variability in demographic factors associated with booster coverage. Higher proportion of persons age ≥65 was positively associated with booster coverage in all 10 Census Regions. In these adjusted models, proportion Asian was also positively associated with booster coverage in 6 out of 10 Census Regions. Proportion Black was associated with lower booster coverage in Los Angeles County only. While proportion of Hispanic/Latinx persons was positively associated with booster coverage in Superior California, Northern San Joaquin Valley, and Southern San Joaquin Valley, it was associated with lower booster coverage in the San Francisco Bay Area (Tables 2a-2b).

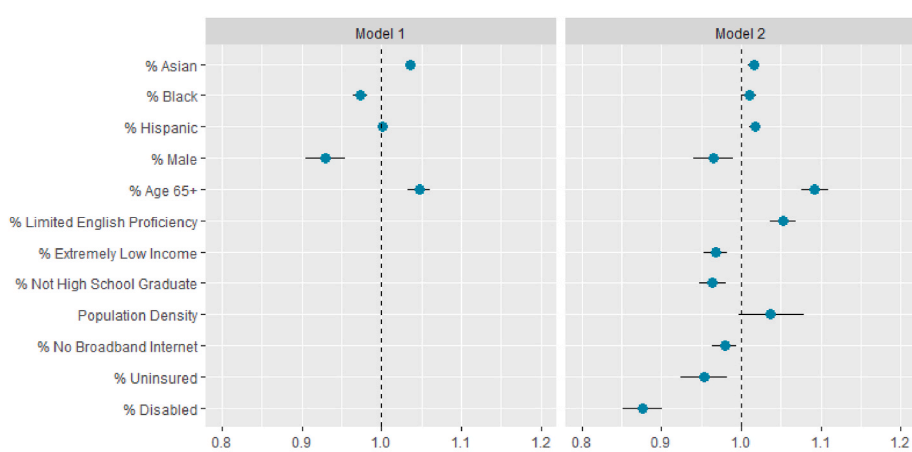

Fig. 1a. Forest plots of minimally adjusted (Model 1) and fully adjusted (Model 2) quasi-Poisson models with ZCTA-level observations for all COVID-19 vaccinations reported in California up to September 21, 2021.[a].

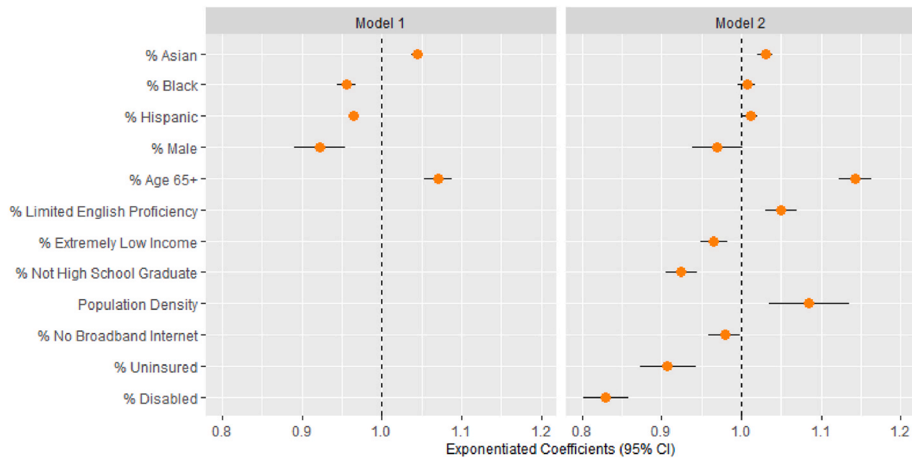

Fig. 1b. Forest plots of minimally adjusted (Model 1) and fully adjusted (Model 2) quasi-Poisson models with ZCTA-level observations for all COVID-19 boosters reported in California up to March 29, 2022.[a].

[a] Data is offset for the natural logarithm of population ≥12 years and adjusted for county.

Table 1a
Distribution of neighborhood characteristics by CA census regions (1–5).

	1 – Superior California	2 – North Coast	3 – San Francisco Bay Area	4 – Northern San Joaquin Valley	5 – Central Coast	Overall
	(N = 246)	(N = 126)	(N = 240)	(N = 139)	(N = 115)	(N = 1634)
	Median	Median	Median	Median	Median	Median
% Fully Vaccinated [a]	55.6	63.9	84.4	54.2	70.6	66.1
% Boosted [b]	31.5	41.7	64.2	27.3	44.7	39.1
% Boosted Among Eligible [c]	50.5	55.5	65.9	41.7	55.5	51.0
% Asian	3.0	2.0	24.5	3.5	4.8	6.8
% Black	1.7	1.0	3.8	1.5	1.9	2.8
% Hispanic/Latinx	13.6	11.9	16.1	27.8	28.6	23.8
% White	74.3	76.7	44.5	59.5	60.5	51.7
% Male	49.9	50.3	49.3	50.2	49.7	49.6
% Age ≥65	19.4	22.9	15.4	15.6	16.8	15.5
% Limited English Proficiency	4.1	3.3	12.8	10.6	8.8	10.5
% Extremely Low Income	13.0	13.5	14.0	11.3	11.6	13.6
% Not High School Graduate	9.2	9.8	6.8	15.0	10.0	11.2
Population Density [d]	26.3	20.9	1360.9	38.0	155.9	386.5
% Foreign Born	7.6	6.4	27.0	14.4	16.2	19.3
% No Broadband Internet	16.8	17.1	8.5	17.3	11.9	13.7
% Uninsured	5.5	6.9	3.3	5.8	6.0	6.1
% Disabled	14.6	15.1	9.0	13.8	10.8	11.0

[a] As of September 21, 2021.
[b] As of March 29, 2022.
[c] Proportion boosted among population of fully vaccinated as of March 29, 2022.
[d] Persons per square kilometer.

On further examination of the significant predictors of booster rates, there were different patterns emerging from the regions with the lowest and highest vaccination rates. In Southern San Joaquin Valley which has the lowest booster coverage, proportion with no high school degree, no broadband internet and disability were associated with lower booster coverage. Yet in the San Francisco Bay Area which has the highest booster coverage, proportion Hispanic/Latinx, extremely low income, and disability were associated with lower booster coverage and proportion of persons with LEP was associated with higher coverage (Tables 2a-2b).

5. Discussion

Our analysis found that neighborhood-level factors appear to be stronger predictors of vaccination coverage than the racial or ethnic composition of neighborhoods. While neighborhoods with a higher proportion of Hispanic/Latinx or Black residents have lower vaccination and booster rates overall, adjustment for neighborhood-level factors accounted for these disparities. Prevailing frameworks around place and health highlight that neighborhood environments are, at least in part, determined by structural racism and subsequent neighborhood disinvestment, thus our results suggest that racial and ethnic disparities in vaccination may be in part due to ongoing and persistent consequences of structural racism (Bailey et al., 2017; Bécares et al., 2022; Brown & Homan, 2022; Egede & Walker, 2020; Johnson, 2020; O'Brien et al., 2020). These findings highlight the need to investigate factors mediating the effect of racism on population-level racial and ethnic health disparities. Our findings also call for a greater focus on neighborhoods with residents facing economic and healthcare access barriers including lower income/educational attainment, higher disability rates, and lack of medical insurance, which may present structural barriers to vaccine access. Our findings are also consistent with other studies that have called for a greater attention to place-based and neighborhood-level data, particularly as public health and population-level interventions and programs are evaluated (Dankwa-Mullan & Perez-Stable, 2016; Khullar & Chokshi, 2020; Kolak et al., 2020).

Table 1b
Distribution of neighborhood characteristics by CA census regions (6–10).

	6 - Southern San Joaquin Valley	7 - Inland Empire	8 - Los Angeles County	9 - Orange County	10 - San Diego - Imperial	Overall
	(N = 136)	(N = 151)	(N = 280)	(N = 88)	(N = 113)	(N = 1634)
	Median	Median	Median	Median	Median	Median
% Fully Vaccinated [a]	53.6	56.7	70.2	71.1	69.5	66.1
% Boosted [b]	27.2	30.5	45.2	46.4	34.6	39.1
% Boosted Among Eligible [c]	41.4	45.5	53.9	56.4	40.5	51.0
% Asian	3.1	4.9	13.7	17.2	8.1	6.8
% Black	1.4	6.2	5.4	2.1	3.6	2.8
% Hispanic/Latinx	58.7	40.6	35.2	19.7	26.7	23.8
% White	28.5	42.0	28.8	48.8	54.4	51.7
% Male	50.8	49.7	49.0	49.2	50.0	49.6
% Age ≥65	11.6	13.2	13.9	14.5	13.9	15.5
% Limited English Proficiency	17.4	10.4	19.9	13.4	10.2	10.5
% Extremely Low Income	14.7	13.1	16.8	13.0	15.1	13.6
% Not High School Graduate	27.8	15.5	13.5	7.3	9.7	11.2
Population Density [d]	56.2	359.3	3013.4	2118.5	842.4	386.5
% Foreign Born	19.9	17.6	32.2	24.6	19.8	19.3
% No Broadband Internet	26.8	14.9	14.2	8.4	9.9	13.7
% Uninsured	8.1	7.8	7.6	5.5	7.0	6.1
% Disabled	12.5	12.0	9.7	8.3	10.5	11.0

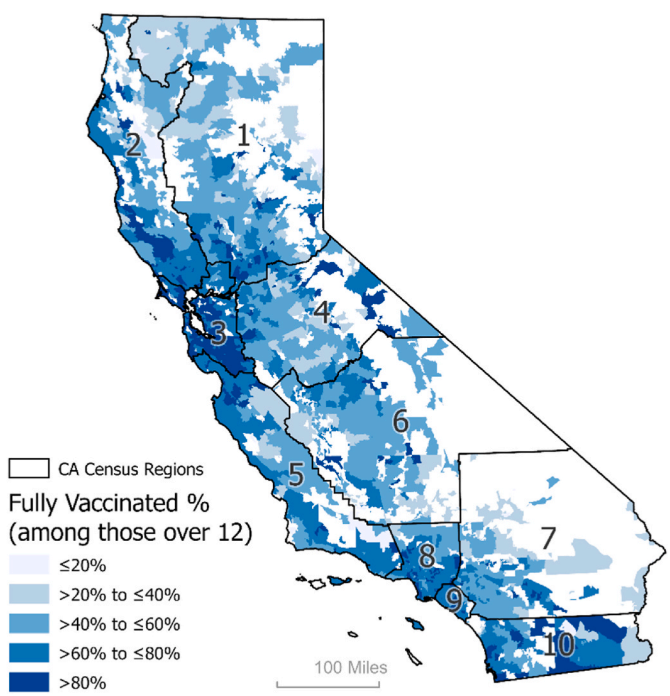

Fig. 2a. Vaccine coverage quintiles among age 12+ across California, overlayed with Census Regions, September 21, 2021.

[a] As of September 21, 2021; [b] As of March 29, 2022; [c] Proportion boosted among population of fully vaccinated as of March 29, 2022; [d] Persons per square kilometer.

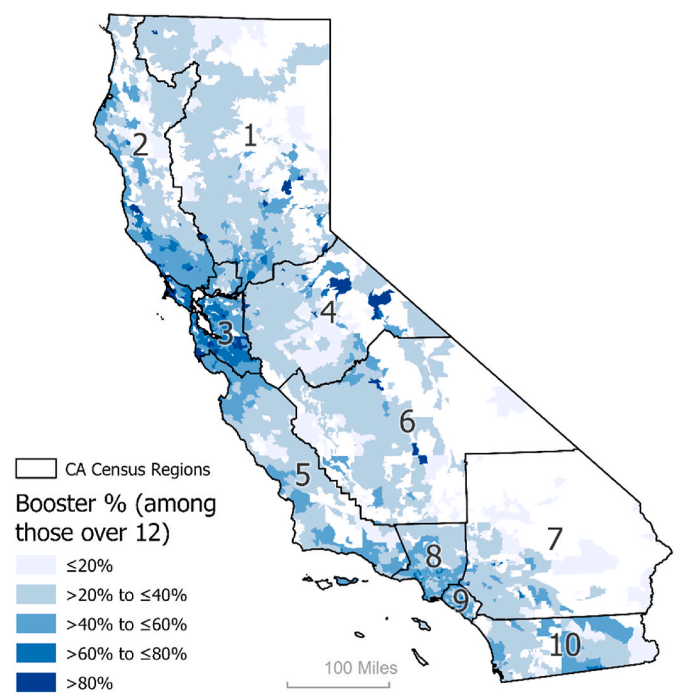

Fig. 2b. Booster coverage quintiles among age 12+ across California, overlayed with Census Regions, March 29, 2022.

We found uninsurance was negatively associated with vaccination, which is aligned with past research suggesting individuals with health insurance are more willing to be vaccinated (Diesel et al., 2021; Wake, 2021). This may be related to insurance providing access to healthcare providers who are a trusted source of information and directly recommend and/or supply vaccines. There is also a clear relationship between immigration status and uninsurance in the U.S., with undocumented residents being one of the largest groups without regular health insurance (Dietz et al., 2022). Research among undocumented populations in the U.S. has identified a common misconception that utilizing healthcare services, including publicly funded COVID-19 testing or vaccination, may jeopardize immigration status (Galletly et al., 2021). These findings support recommendations for targeted outreach via trusted providers developed specifically for uninsured and undocumented individuals to combat misconceptions about ineligibility or fears of immigration consequences (Barry et al., 2022; Galletly et al., 2021).

We also identified higher disability rates were associated with reduced COVID-19 vaccinations and boosters, despite this population being prioritized for vaccination outreach and targeted by vaccination campaigns (California Department of Public Health, 2021b). This disparity has been identified in other research focused at the county-level (Barry et al., 2022) and may be related to accessibility throughout the entire "vaccination pathway," defined by Rotenbuerg et al. as communications, booking, physical accessibility, and environmental accessibility (Rotenberg et al., 2021). This finding highlights the need for consistent and accessible public messaging to clearly define

Table 2a
Coefficients of COVID-19 Boosters in California Census Regions (1–5), Fully Adjusted [a,b].

	1 - Superior California	2 - North Coast	3 - San Francisco Bay Area	4 - Northern San Joaquin Valley	5 - Central Coast	Overall
	(N=246) Est. [95% CI]	(N=126) Est. [95% CI]	(N=240) Est. [95% CI]	(N=139) Est. [95% CI]	(N=115) Est. [95% CI]	(N=1634) Est. [95% CI]
% Boosted [c]	**31.5%**	**41.7%**	**64.2%**	**27.3%**	**44.7%**	**39.1%**
% Asian	1.17 [1.13-1.22]	1.02 [0.95-1.09]	0.99 [0.97-1.01]	1.17 [1.11-1.23]	0.95 [0.88-1.04]	1.03 [1.02-1.04]
% Black	0.95 [0.89-1.02]	0.98 [0.80-1.19]	1.01 [0.99-1.04]	0.92 [0.83-1.02]	0.88 [0.74-1.03]	1.01 [1.00-1.02]
% Hispanic/Latinx	1.10 [1.05-1.15]	0.96 [0.90-1.03]	0.95 [0.92-0.97]	1.12 [1.07-1.17]	0.96 [0.93-1.00]	1.01 [1.00-1.02]
% Male	0.98 [0.86-1.11]	1.07 [0.97-1.17]	1.05 [0.98-1.12]	1.06 [0.96-1.16]	0.92 [0.82-1.04]	0.97 [0.94-1.00]
% Age ≥65	1.12 [1.05-1.20]	1.07 [1.02-1.13]	1.12 [1.07-1.17]	1.16 [1.06-1.25]	1.09 [1.02-1.18]	1.14 [1.12-1.16]
% Limited English Proficiency	0.91 [0.81-1.01]	1.18 [1.03-1.35]	1.08 [1.01-1.15]	1.06 [0.97-1.16]	1.26 [1.11-1.44]	1.05 [1.03-1.07]
% Extremely Low Income	0.99 [0.94-1.05]	0.95 [0.89-1.03]	0.95 [0.91-0.98]	0.94 [0.86-1.04]	0.99 [0.92-1.06]	0.97 [0.95-0.98]
% Not High School Graduate	0.92 [0.83-1.03]	0.91 [0.82-1.01]	0.96 [0.90-1.03]	0.75 [0.70-0.81]	0.89 [0.80-0.99]	0.93 [0.91-0.95]
Population Density [d]	1.52 [1.02-2.26]	1.53 [0.95-2.43]	0.98 [0.91-1.06]	0.74 [0.53-1.03]	1.52 [1.12-2.04]	1.08 [1.03-1.14]
% No Broadband Internet	0.96 [0.88-1.04]	0.98 [0.92-1.04]	0.98 [0.93-1.02]	1.02 [0.96-1.08]	0.90 [0.83-0.96]	0.98 [0.96-1.00]
% Uninsured	0.77 [0.65-0.91]	0.84 [0.74-0.94]	1.01 [0.91-1.13]	1.02 [0.88-1.17]	0.89 [0.81-0.99]	0.91 [0.87-0.94]
% Disabled	0.84 [0.76-0.94]	0.94 [0.86-1.02]	0.91 [0.83-0.99]	0.93 [0.82-1.05]	1.09 [0.95-1.24]	0.83 [0.80-0.86]

[a] Green shading represents significant positive correlation and orange shading represents significant negative association defined as $p < .05$.
[b] Data is offset for the natural logarithm of population age ≥12 years and adjusted for county.
[c] As of March 29, 2022.
[d] Persons per square kilometer.

Table 2b
Coefficients of COVID-19 Boosters in California Census Regions (6–10), Fully Adjusted [a,b].

	6 - Southern San Joaquin Valley	7 - Inland Empire	8 - Los Angeles County	9 - Orange County	10 - San Diego - Imperial	Overall
	(N=136) Est. [95% CI]	(N=151) Est. [95% CI]	(N=280) Est. [95% CI]	(N=88) Est. [95% CI]	(N=113) Est. [95% CI]	(N=1634) Est. [95% CI]
% Boosted [c]	**27.2%**	**30.5%**	**45.2%**	**46.4%**	**34.6%**	**39.1%**
% Asian	1.11 [1.05-1.16]	1.14 [1.08-1.20]	1.05 [1.04-1.07]	1.10 [1.06-1.14]	1.01 [0.97-1.05]	1.03 [1.02-1.04]
% Black	0.95 [0.89-1.02]	0.99 [0.93-1.05]	0.98 [0.96-0.99]	0.94 [0.79-1.12]	0.95 [0.87-1.03]	1.01 [1.00-1.02]
% Hispanic/Latinx	1.05 [1.01-1.08]	1.03 [0.98-1.08]	1.00 [0.99-1.02]	1.02 [0.99-1.05]	1.02 [0.98-1.05]	1.01 [1.00-1.02]
% Male	0.93 [0.84-1.02]	0.92 [0.83-1.01]	1.07 [1.00-1.14]	0.93 [0.83-1.04]	0.87 [0.75-1.01]	0.97 [0.94-1.00]
% Age ≥65	1.25 [1.15-1.36]	1.26 [1.20-1.33]	1.17 [1.11-1.23]	1.10 [1.05-1.16]	1.23 [1.13-1.34]	1.14 [1.12-1.16]
% Limited English Proficiency	1.06 [1.00-1.13]	1.07 [0.98-1.15]	0.96 [0.93-0.99]	1.01 [0.92-1.11]	1.23 [1.14-1.34]	1.05 [1.03-1.07]
% Extremely Low Income	0.98 [0.92-1.05]	0.96 [0.88-1.04]	0.97 [0.94-1.01]	0.91 [0.86-0.96]	1.02 [0.92-1.13]	0.97 [0.95-0.98]
% Not High School Graduate	0.92 [0.86-0.99]	0.93 [0.85-1.03]	0.97 [0.93-1.00]	0.96 [0.88-1.06]	0.85 [0.77-0.95]	0.93 [0.91-0.95]
Population Density [d]	1.07 [0.79-1.46]	1.45 [0.92-2.26]	1.07 [0.98-1.16]	0.88 [0.68-1.14]	2.14 [1.53-3.00]	1.08 [1.03-1.14]
% No Broadband Internet	0.91 [0.86-0.97]	0.99 [0.92-1.08]	1.01 [0.97-1.04]	1.06 [0.99-1.13]	0.93 [0.82-1.06]	0.98 [0.96-1.00]
% Uninsured	0.98 [0.85-1.13]	0.96 [0.81-1.14]	0.98 [0.90-1.06]	0.94 [0.83-1.06]	0.77 [0.65-0.90]	0.91 [0.87-0.94]
% Disabled	0.84 [0.75-0.95]	0.82 [0.72-0.94]	0.85 [0.79-0.91]	0.85 [0.75-0.96]	0.74 [0.63-0.87]	0.83 [0.80-0.86]

[a] Green shading represents significant positive correlation and orange shading represents significant negative association defined as $p < .05$.
[b] Data is offset for the natural logarithm of population age ≥12 years and adjusted for county.
[c] As of March 29, 2022.
[d] Persons per square kilometer.

priority populations and provide instructions on how to access vaccinations, as well as pop-ups and outreach events tailored to serve the disability community (Association of University Centers on Disabilities, 2021; Rotenberg et al., 2021).

We found that the same neighborhood social determinants of health associated with vaccination were also associated with boosters, except for population density, which was a predictor of booster coverage only. Other researchers have identified that the gap in vaccination between urban and rural areas within the United States has more than doubled between April 2021 and January 2022 (Saelee et al., 2022). More research is warranted to explore whether the disparity in booster coverage within lower density ZCTAs in California is an issue of timing, access, or demand (potentially due to perceived risk or political affiliation (Albrecht, 2022)). We adjusted for county to account for differential COVID-19 policies and practices, however factors influencing place-based outcomes and behaviors, for example structural racism, exist on multiple spatial scales (Brown & Homan, 2022). Despite a focus on more granular ZCTA-level variables to examine neighborhood, we also opted to stratify by regions based on the size and heterogeneity of the state in terms of population and political ideology. Our results highlight the wide range of vaccination and booster coverage across regions of California. For example, while rates of full vaccination in the San Diego-Imperial region were higher than the state median, booster rates among both the total and eligible population were notably low. This disparity may be due to challenges capturing an accurate denominator in this region of the state, where every year more than 90 million people cross the Mexico-U.S. border into San Diego or Imperial Counties for work, education, healthcare, and recreation (Gutiérrez et al., 2021). More research is needed to determine whether low booster coverage in this region can be attributed mainly to numerator and denominator mismatch, as has been the case in other parts of the U.S., (Kelman, 2022), or whether there is a deeper structural cause of the change in rates between vaccinations and booster doses.

Our results also highlight the regional variability of factors associated with booster coverage. While a higher proportion of Hispanic/Latinx residents was associated with increased booster coverage in several regions of California, it was linked to lower booster coverage in the San Francisco Bay Area – the region with the highest overall booster rate, even after adjusting for other social vulnerabilities. Despite equity-focused initiatives to reduce vaccination disparities in the Bay Area, some local research has highlighted lower intent to vaccinate among Hispanic/Latinx Bay Area residents compared to Latino communities in other parts of the U.S. (Wojcicki et al., 2022/06) Community-based strategies at the neighborhood level have proven successful in the Bay Area to improve vaccination rates among Hispanic/Latinx residents, but they should address access and trust-related barriers, be tailored to neighborhoods, and work collaboratively with trusted messengers and social networks (Marquez et al., 2021). Finally, it will be important in evaluating equity in vaccination efforts to disentangle SDOH variables in future work. We found higher rates of vaccination among ZCTAs with higher LEP populations, and more research is needed to understand whether this is tied to urban dwelling populations or a result of successfully addressing linguistic access barriers.

Our study has some limitations. Vaccination data was only available at ZIP code level and so usage of data at ZCTA level was necessary. However, since ZIP codes are mail delivery routes, ZCTAs may imperfectly identify those areas and the people who live there (United States Censes Bureau, 2022). Although an "infectious process" may not be playing the same role in vaccinations as in the spread of COVID itself, we considered using a spatial autoregressive model (SAR), to account for the influence of spatial proximity. However, since ZCTA coverage is discontinuous (i.e., some areas are not covered), using a SAR might present greater challenges than using it on a study based on census tract data, which provide continuous coverage and so was not feasible in the current study. This study focused on neighborhood-level associations and is not intended to be interpreted at the individual level. Variables such as vaccine sentiment and beliefs were not available for these analyses, nor were data on local vaccination infrastructure. We were also unable to include occupation or essential worker data, as standardized ZCTA-level variables on occupation were unavailable. Many people relocated during the pandemic, so the estimate of the population aged $\geq$12 years may not accurately reflect the population since population counts were calculated from the 2015–2019 ACS from before the COVID-19 pandemic. Finally, the California context is not fully generalizable nationwide, but the size and heterogeneity of this state is likely broadly informative.

5.1. Conclusions

A key strength of this research is the use of granular geographic data at the ZCTA level, unlike most current research which uses county averages, obscuring the true neighborhood-level heterogeneity of COVID-19 vaccination. Under-vaccinated clusters of the population ultimately increase disease transmission throughout the state, including breakthrough cases among vaccinated individuals (Tiu et al., 2022). By using vaccination and booster data at the zip code level, and stratifying by region, we were able to identify neighborhood characteristics that may be useful to inform local public health department vaccination strategies for considering and implementing population-level strategies to improve health and healthcare. Changes in individual behavioral and clinical programs are also necessary to reduce disparities but may not be effective in absence of population-level interventions. The COVID-19 pandemic has demonstrated that blending clinical and public health data to inform interventions is truly essential to improving health equity.

Author's contributions

Debora L Oh: Conceptualization, Methodology, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Kathryn E Kemper:** Conceptualization, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Project administration. **Dan Meltzer**: Conceptualization, Methodology, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Alison J Canchola:** Methodology, Writing - Review & Editing. **Kirsten Bibbins-Domingo**: Conceptualization, Writing - Review & Editing, Supervision, Funding acquisition. **Courtney R Lyles:** Conceptualization, Writing - Original Draft, Writing - Review & Editing, Supervision, Funding acquisition.

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Access to data

DO had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Declaration of competing interest

None to declare.

Data availability

All data used in this analysis is publicly available at the sources cited in Methods section.

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