7-2023

What Explains Spatial Cariations of COVID-19 vaccine hesitancy?: a social-ecological-technological systems approach

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Citation Details

Pallathadka, A. K., Chang, H., & Han, D. (2022). What explains spatial variations of COVID-19 vaccine hesitancy?: A social-ecological-technological systems approach. Environmental Research: Health.

ENVIRONMENTAL RESEARCH
HEALTH

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To cite this article: Arun Pallathadka *et al* 2023 *Environ. Res.: Health* **1** 011001

IOP Publishing *Environ. Res.: Health* **1** (2023) 011001 https://doi.org/10.1088/2752-5309/ac8ac2

ENVIRONMENTAL RESEARCH
HEALTH

RECEIVED
29 April 2022

REVISED
20 July 2022

ACCEPTED FOR PUBLICATION
18 August 2022

PUBLISHED
1 November 2022

LETTER

What explains spatial variations of COVID-19 vaccine hesitancy?: a social-ecological-technological systems approach

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Keywords: COVID-19, vaccine hesitancy, socio-ecological-technological systems framework, GWR, USA

Abstract

While COVID-19 vaccines have been available since December 2020 and efforts have been made to vaccinate the maximum population, a large number of people are continuing to be hesitant, prolonging the pandemic in the US. While most previous studies investigated social, economic, and demographic variables that are associated with COVID-19 vaccine hesitancy, we added ecological and technological variables to better understand the spatial variations of vaccine rates in the contiguous United States using spatial regression and geographically weighted regression (GWR) models. We aim to identify spatially varying social, ecological, and technological factors that are associated with COVID-19 vaccination rates, which can aid in identifying and strengthening the public health system and vaccination programs that can eventually facilitate and overcome vaccination hesitancy. We found six statistically significant predictors; two predictors, % Republican voters ($r = 0.507$, $p < .001$) and % Black population ($r = -0.360$, $p < .001$) were negatively correlated with the vaccination rates, whereas four remaining predictors, % Population with college degree ($r = 0.229$, $p < 001$), NRI Score ($r = 0.131$, $p < .001$), % Population with broadband access ($r = 0.020$, $p < 001$), and Health facilities per 10 000 population ($r = 0.424$, $p < 001$) were positively correlated with the vaccination rates at the county level. GWR results show spatially varying relationships between vaccination rate and explanatory variables, indicating the need for regional-specific public health policy. To achieve widespread vaccination, addressing social, ecological, and technological factors will be essential. We draw particular attention to the spatial variances even among positively and negatively associated factors. This research also calls for a reexamination of existing practices, including vaccination communication and other public health policies, local and national public health organizations, telecommunications agents, and mobilization of resources by the public and private sectors.

1. Introduction

Vaccine hesitancy refers to a delay in accepting or refusing vaccinations despite vaccine services being available (MacDonald 2015, Troiano and Nardi 2021). COVID-19 vaccine hesitancy is a serious challenge globally, despite attempts by healthcare providers to vaccinate the majority of the population. This hesitancy has resulted in a resurgence of COVID-19 cases in many parts of the world. In the United States (US) alone, there were nearly 5 million new cases in the first week of 2022 (CDC 2022a). According to recent vaccination statistics, regions with lower vaccination rates have greater social and racial disparities (Attonito *et al* 2021, Dorélien *et al* 2021, Mollalo and Tatar 2021). Multivariate research revealed a significant link between the number of vaccination sites in a ZIP code and race and ethnicity, but a lesser association with the percentage of residents below the poverty level (Attonito *et al* 2021). Disease exposure and mortality rates are more in racial and ethnic minorities, as well as in socioeconomically deprived communities than in other groups (Tribby and Hartmann 2021). Long-standing socioeconomic and health inequities among African Americans, Hispanics, Native Americans, and Alaska Natives resulted in increased virus exposure, limited access to care, and increased risks of developing more severe diseases (Tai *et al* 2021).

Globally, vaccine hesitancy has been fueled by ills such as anti-science movements and pseudoscientific arguments (Cornwall 2020, Wang *et al* 2020), despite the fact that COVID-19 vaccination has been considered safe and effective (Sultana *et al* 2020, Thomas *et al* 2021). Many factors potentially contribute to vaccine hesitancy, such as political affiliation, religious beliefs, race, income, and overall distrust toward government. The facilitators of vaccine hesitancy can also be exacerbated by factors such as demonizing immunity through internet conspiracy blogs and websites (Muric *et al* 2021). Prior to COVID-19 pandemic, several studies have focused on general vaccine hesitancy and dilemma (Facciolà *et al* 2019, Kabir and Tanimoto 2020, 2021, Sultana *et al* 2020). For instance, the cyclic mean-field model developed by Kabir and Tanimoto (2021) explores the sensitivity of vaccine acceptance based on social interactions. Another separate study by Kabir (2021) analyzes the evolutionary game theory and reflects on how individual vaccination practices prioritize selfish interest above the collective good, while Facciolà *et al* (2019) emphasize the importance of health education and communication in promoting vaccinations for preventable diseases.

However, only a handful of studies have thoroughly evaluated factors relating to COVID-19 vaccination and hesitancy. Mollalo and Tatar (2021), for instance, conducted a spatial epidemiological study in the continental US to evaluate the socioeconomic drivers of the COVID-19 vaccination rate. Their findings show that the geospatial disparity in COVID-19 vaccination rate is strongly positively linked to per capita income but negatively related to the uninsured rate. They suggested that higher-resolution spatial analysis at different scales be carried out, as well as environmental, demographic, and health-related variables. Hernandez *et al* (2021) examined how community-based walk-up sites in New Orleans, LA, increased coverage and utilization of Covid-19 testing services for vulnerable and hard-to-reach individuals. Patients who were African American or Asian were substantially more likely, 14.7% and 53.0%, respectively, than whites to use the nearest walk-in site, because they traveled a shorter distance to get tested. The same effect was shown in elderly people, who were much less likely to have their blood tested at locations further away from their homes. Across sociodemographic categories, persistent differences exist in vaccine behavior and views. Due to their confidence and caution, Blacks are more likely than whites to develop vaccine hesitancy. While vaccine hesitancy among African Americans has decreased considerably over time, it varies little by state (Liu and Li 2021). While recent data suggests that the racial difference in COVID-19 vaccine uptake is reducing, in most reporting states, white individuals still have a higher vaccination rate than the Hispanic and Black populations (Ndugga *et al* 2021).

In the US, studies have shown the role of political partisanship in vaccine hesitancy (Allcott *et al* 2020, Grossman *et al* 2020). Geographical accessibility to vaccination facilities and resources is also becoming increasingly frequent in recent literature (Mohammadi *et al* 2021, Mollalo *et al* 2021). Thus, a comprehensive spatial analysis is required to improve policymakers' insights into vaccination programs. Although the relationship of certain socioeconomic variables to vaccination rates is well established, several variables, including those beyond the socioeconomic domain, have not been well researched for vaccine rates. To fill this research gap, we perform spatial analysis to understand COVID-19 vaccine rates in US. Using complete vaccination data at the county level until the end of December 2021, we seek to answer where and why vaccine hesitancy persists across the country using a Social-Ecological-Technological Systems (SETS) framework (Grimm *et al* 2017, Chang *et al* 2020, 2021). As there is a scarcity of research on the environmental and technological aspects of COVID-19 vaccine spatial modeling in US, this study can serve as a geospatial reference to aid public health decision-makers in developing region-specific policies and monitoring vaccination programs. We also focus on additional socioeconomic variables (e.g. % Female population of fertility age, % Population with bachelor's degree or higher) that previous studies did not investigate.

Research questions:

(a) Where are the geographic hotspots of low and high vaccination rates?
(b) What are the SET factors explaining the spatial variations of low and high vaccination rates?
(c) How does the relationship between vaccination rates and explanatory variables vary over space?

2. Study area

Our study areas consist of 3108 counties and county-equivalent administrative units in the contiguous US (CONUS). US represents a various social, political, ecological, technological spectrum, and the county is the smallest spatial unit that vaccination rate and other explanatory variables are readily available. A total of 135 counties were excluded (out of 3243 total counties or county-equivalent) either because they were not part of the CONUS or because the vaccination data was not available.US is leading the global charts on COVID infections, and the CONUS region is responsible for over 95% of the cases as of 31 December 2021 (Coronavirus Resource Center 2021). The US federal government, in conjunction with state and local governments, has ensured that over 60% of the population are fully vaccinated with two doses as of 31 December 2021 (figure 1). As shown in figure 1, there is a substantial spatial variation of the vaccination rate. As such, we examined what factors explain vaccination rates or hesitancy in the CONUS counties for which recent data is available.

3. Materials and methods

3.1. SETS framework to analyze vaccination rates/hesitancy

Many recent studies have focused on socioeconomic factors that contribute to vaccination rates (Attonito *et al* 2021, Dorélien *et al* 2021, Liu and Li 2021, Mollalo and Tatar 2021). While socioeconomic factors are important, we believe that environmental and technological dimensions can provide additional insights into the vaccination hesitancy in society (Runkle *et al* 2020, Gatti *et al* 2021). The SETS framework has proven utility in various urban vulnerability and risk analysis studies in the US (Grimm *et al* 2017, Chang *et al* 2020, 2021, Kim *et al* 2021). We propose this framework to evaluate it for a public health vulnerability analysis for the first time, but given that public health is indeed related to the environment and technology, there is a clear need to include these dimensions in the analysis (table 1). We also propose to include new social variables such as political belief (via 2020 Presidential voting numbers) and the female population of fertility age for the first time in a comprehensive manner. No studies have analyzed the entire 2021 vaccination rates from a national political belief perspective; other than Buckman *et al* (2020), which focused on local political trends in North Carolina, there is only one national study that related vaccination rates to national political trends halfway into the vaccination efforts in 2021 (Albrecht 2022). We believe that many events leading up to the 2020 Presidential election also led to the politicization of vaccines, which became a symbol of a battle where science meets politics and ideology. Such political conflicts adversely affect the ability to develop evidence-based interventions. There was a lot of anti-vaccine rhetoric in 2020 and 2021 among the Republican leadership, politicians, and other popular figures (Allcott *et al* 2020, Lerer 2021). As such, it is worthwhile to investigate its link to vaccination rates and hesitancy; thus, we included *political belief* as one of the variables. In addition, we introduce the National Risk Index (NRI), a tool designed by the Federal Emergency Management Agency (FEMA) to identify areas that are at risk of 18 natural hazards, as an ecological variable (FEMA 2021). Additionally, no study has associated vaccination rates with farmlands. In terms of technological dimension, we include impervious surface as a proxy for urbanization that is likely to promote vaccination sites, and polluting sites/factories as a proxy for potential COVID vaccination deserts. Finally, we also hypothesize that greater internet access as a proxy for information access is key to higher vaccination rates, which has not been evaluated prior to this study.

3.2. Data

We obtained the COVID vaccination data (December 2020–December 2021) at the county level from CDC and US Census Bureau (US Census Bureau 2019, CDC 2022b), which serve as the dependent variable in our regression analysis. The COVID vaccination data is a weekly aggregate at the county level from December 2020 to December 2021, therefore it is the total % of people vaccinated per county. The 2020 election data was downloaded from the MIT Election Data and Science Lab (MIT 2018). Additional social variables were obtained from the US Census Bureau, ACS-5 yr estimates from 2019 (US Census Bureau 2019). Both *farmland* and *impervious surface* were derived from National Land Cover Data, 2019 (Dewitz 2021). The NRI data was downloaded from FEMA (FEMA 2021). The *factories* data was aggregated from the US Energy Information Administration using multiple layers—coal plants and general manufacturing facilities (EIA 2020). The health facilities data (summarized version) was created by National Council for Prescription Drug Programs and obtained from Dr Inmaculada Hernandez at the University of California at San Diego. All geospatial data were either obtained or summarized at the county level.

3.3. Methods

3.3.1. Hotspot analysis

A hotspot is an area that has a higher concentration of occurrences compared to the expected number given a random distribution of occurrences. Hotspot detection evolved from the study of point distributions or spatial arrangements of points in space (Chakravorty 1995). A comprehensive spatial randomness model is used to compare the density of points inside a specific area. The hotspot model was run on ArcMap 10.8.1 to calculate the Getis-Ord Gi* statistic (ESRI 2020). The Gi* statistics is given as:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \overline{X} \sum_{j=1}^{n} w_{i,j}}{\sqrt[S]{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}} \quad (1)$$

where, x_j is the attribute value for feature j, $w_{i,j}$ is the spatial weight between feature i and j, n is equal to the total number of features.

To model the spatial relationship, we selected the *Contiguity Edges and Corners/Queen's Case* rule, which constructs neighbors from polygons that share either a boundary (edge) or a corner (node) (Lloyd 2010). This method combines the Bishop and Rook

Table 1. SET variables to explain the COVID vaccination acceptance/hesitancy.

Category	Variable and hypothesized relationship	Source	Justification	References
Social	% Voters who voted for Republican Presidential Nominee in 2020 (−)	MIT Election Data and Science Lab	Republican voters are less likely to be vaccinated due to misconceptions about vaccine	Buckman *et al* 2020, Albrecht 2022
	% Population Aged 65 and Over (+)	ACS 2019, US Census Bureau	The elderly population is more likely to be vaccinated because of age-related health concerns	Chakraborty *et al* 2021, Zanettini *et al* 2021
	% Population Change (2010–2020) (+)	ACS 2010 and ACS 2020, US Census Bureau	Places with a greater number of people are more likely to offer and accept vaccinations due to availability and access	Jung and Albarrac 2021
	% Population (Aged 18 or Over) with Bachelor's Degree or Higher (+)	ACS 2019, US Census Bureau	The educated population is more likely to receive vaccines due to relatively higher awareness	Ehde *et al* 2021, Holeva *et al* 2022
	% Minority by each racial group (−)	ACS 2019, US Census Bureau	Minorities are less likely to have equal access to vaccines	Attonito *et al* 2021, Mollalo *et al* 2021, Pallathadka *et al* 2021
	% Female Population of Fertility Age (15–44) (−)	ACS 2019, US Census Bureau	Females of fertility age are less likely due to concerns about reproductive health	Markert *et al* 2021, Holeva *et al* 2022
	Median Household Income (+)	ACS 2019, US Census Bureau	Wealthy people are more likely to receive vaccines due	Mollalo *et al* 2021
Ecological	National Risk Index (+)	FEMA	The communities that are at risk of natural hazards are more likely to receive vaccines because of higher risk perception, which can indicate proactive preparedness to disasters including public health crisis	Nuzzo *et al* 2019, Joshi *et al* 2021
	% Farmland (−)	NLCD, 2019	A large amount of green space promotes good circulation of air	Chicas *et al* 2022
Technological	% Population with Broadband Access (+)	FCC, 2018 www.fcc.gov/form-477-county-data-internet-access-services	People with high-speed internet access are more likely to have greater digital literacy and access to information	Horrigan 2010, Scherer and Pennycook 2020
	Health Facilities (+)	National Council for Prescription Drug Programs	The higher density of health facilities makes it easier to get vaccinated	Berenbrok *et al* 2021
	% Impervious Surface (+)	NLCD, 2019	Higher impervious surface indicates urbanization, where vaccination rates are high due to access and awareness	Cerio *et al* 2021
	Factories (−)	Energy Information Administration (EIA), 2021	Industrial areas have more air pollution and are usually located in undesirable areas, where marginalized communities often live, making them less likely to get the vaccination	Wu *et al* 2020

relationships into a single measure, accounting for spatial contiguity by considering adjacent neighbors in all directions (Tsai *et al* 2009, Ghosh *et al* 2021).

3.3.2. Spatial regression model

Because vaccination rate shows strong spatial autocorrelation, we ran three different regression models to examine demographic, geographic, and situational factors explaining vaccine acceptance/hesitancy. These variables are broadly classified into three main domains: Social (S), Ecological (E), and Technological (T). The baseline model we adopted was the conventional Ordinary Least Square (OLS) model. An OLS model is most commonly used for comparing variables and relationships. We initially ran Exploratory Regression on ArcMap 10.8.1 (ESRI 2020) to determine the best combination of exploratory variables to use in the OLS model by avoiding multicollinearity (VIF > 10; Salmerón *et al* 2018). Because OLS models do not take into account spatial autocorrelation that many spatial data might present, they have limited utility for explaining spatial phenomena. In contrast, spatial regression models, by considering spatial autocorrelation in either dependent (spatial lag models) or residuals (spatial error models), are capable of addressing the limitation of OLS. We thus use the same set of explanatory variables for running spatial regression models on GeoDa version 1.20 (Anselin *et al* 2006). By comparing R^2 and AIC values, we selected spatial error models over spatial lag models for the final model comparison between OLS and spatial regression models. The form of spatial error regression is as follows:

$$Yi = Xi\beta i + \varepsilon \qquad \varepsilon = \lambda W\varepsilon + \xi \tag{2}$$

where, Yi is the vaccination rate at county i, $Xi =$ independent variable at county i, $\beta i =$ regression coefficient, $\varepsilon =$ random error terms, $\lambda =$ spatial autoregressive coefficient, $W\varepsilon =$ spatially lagged error term, $\xi =$ homoscedastic and independent error term.

3.3.3. Geographically weighted regression

GWR is a local spatial regression method with an objective to identify and quantify the spatial correlates of an independent variable event based on spatial proximity or distance among observations (Brunsdon *et al* 1996, Sassi 2010). GWR has been used for understanding spatial non-stationarity (the existence of different relationships at different points in space) in environmental and epidemiological studies (e.g. Mollalo and Tatar 2021). The GWR-gaussian scheme is an ideal method for normally distributed data. The Gaussian weighting scheme offers the regression feature (feature i) a weight of one, while the weights for the surrounding features (j features) steadily decrease as the distance from the regression feature increases. We used adaptive bandwidth to create weight metrics because county size varies over CONUS. The GWR analysis was conducted in ArcGIS Pro 2.8 (ESRI 2021). The general form of a GWR model is as follows:

$$y_i = \beta_{i0} + \sum_{j=1}^{p} \beta_{ij} x_{ij} + \varepsilon_i \tag{3}$$

where y_i represents vaccination rate at county i, β_{i0} is the intercept for county i, β_{ij} is the estimation of coefficient for jth explanatory variable, X_{ij} is the jth explanatory variable at county i, p is the number of explanatory variables, ε_i is the error term in the model estimates.

3.3.4. GIS analysis and mapping

ArcMap 10.8.1 (ESRI 2020) was used to map local R^2 values that show the goodness of fit in GWR models. We also mapped the coefficient values of the statistically significant explanatory variables at each county using local t-statistical values. Statistically insignificant counties are shown as white.

4. Results

4.1. Spatial patterns of vaccination rate

As shown in figure 1, there exists a distinct spatial pattern of vaccination rate in CONUS. Both counties with high vaccination rates and low vaccination rates are spatially clustered, creating hotspots and coldspots. The hotspot analysis of vaccination rates displays six regions with high vaccinations—Pacific Northwest, Southern California, Southwestern border areas, Navajo Nation, the Upper Midwest, Northeast, and Southern Florida. Similarly, vaccine hesitancy (cold spots) is observed in the Northern Mountain region (Montana, North Dakota, Nebraska, Wyoming), the inner Pacific West (California, Nevada), Missouri, and Georgia.

4.2. OLS and Spatial regression analysis

The six statistically significant explanatory variables display distinct spatial patterns in figure 2. Percent republication voters and Black population maps show strong spatial clustering. Percent Republican voters are higher in the inner mountain west, south, and central mid-west, while percent Black population is predominantly concentrated along the southeast coast. NRI scores are higher in the southwest, along the southeast coast, and the major rivers. Percent population with broadband access is high in the Pacific Northwest, southwest, northeast, upper mid-west, and Florida and Texas counties. Health facilities per 10 K population variable are somewhat randomly distributed, while hotspots are found in the far northeast and the Ohio Valley.

Table 2 shows the results of regression analysis in both OLS and spatial regression. In OLS, Vaccination rates are significantly negatively associated with %

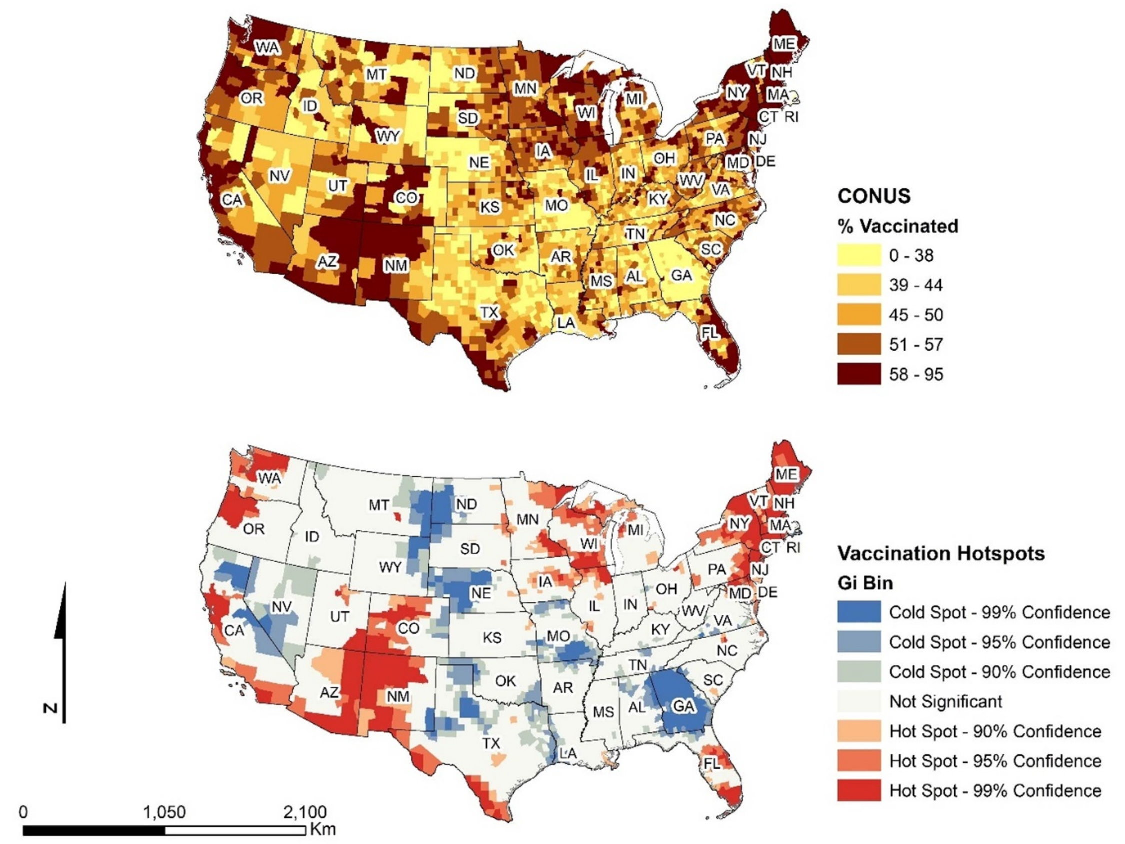

Figure 1. Vaccination rates and vaccination hotspots in the CONUS. The map was created in ArcMap 10.8.1. As of 31 December 2021.

Republican voters (−0.50) and % Black (−0.36) population, whereas they are positively associated with % Population with a college degree (0.22), NRI (0.13), % Population with broadband internet access (0.02) and Counties with a greater number of per capita health facilities (0.42). The Spatial Error (SER) model yielded similar results but, with a significant spatial autoregressive coefficient (0.478), had an overall better fit (58%) compared to the OLS model (47%) and the Spatial Lag model (52%) (not shown).

4.3. GWR analysis

The GWR model explained 76% of the variation of vaccination rate, which was much higher than the baseline OLS model (table 3). The GWR model reported higher local R-squared values in the following regions: the Mountain West (e.g. Montana, Idaho, Utah, Colorado), the Southwest (e.g. Arizona, New Mexico), parts of the South (e.g. Florida, Louisiana), and the Midwest (Wisconsin, Minnesota, Indiana, Ohio) (figure 3), implying improved model performance and better fit. Relatively lower local R-squared values were observed in the following regions: New England (e.g. Vermont, New Hampshire), parts of the South (e.g. Tennessee), and most of the Great Plains (e.g. Kansas, Nebraska), implying that the model is not a perfect fit, but a reverse relationship may be considered.

As shown in figure 4, all explanatory variables show both positive and negative signs of coefficient values. Vaccine hesitancy is strong among Republican voters as shown by both OLS (−0.507, $p < 0.01$) and GWR models. The strong negative association is visible (figure 4) in many Republican counties across the nation, especially in the Mountain States (e.g. Montana, Wyoming), Southwest (e.g. Arizona, New Mexico), and the American South (e.g. Louisiana, Georgia, Florida). In the Northeast, however, many Republican counties in Virginias, New Jersey as well as in New England states such as Maine and Vermont, do show a positive association with vaccination rates, perhaps reflecting a persuasive population of libertarian-leaning or moderate Republicans. Overall, the black population is also negatively associated with vaccination rates, and a strong negative association is found in the South (e.g. Alabama, Georgia), Mountain States (e.g. Colorado, Wyoming), along the Southwest (e.g. Arizona, New Mexico) as well as the Pacific Northwest (e.g. Washington, Oregon)—although results for the West are mixed, especially in some Montana and Nevada counties, indicating that this relationship may vary by state and/or region (figure 4). Another strong predictor of vaccination hesitancy is college education or a population with at least a bachelor's degree. Not surprisingly, the most highly educated demographics are

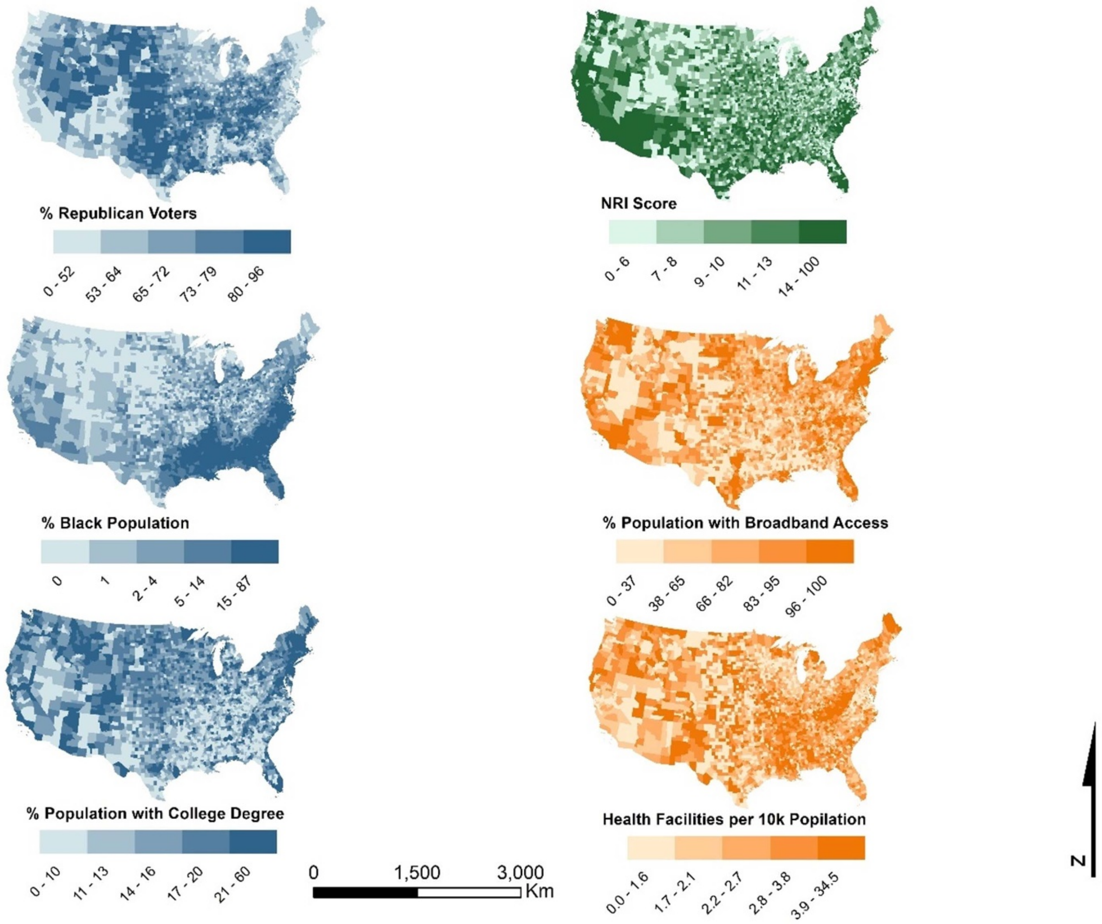

Figure 2. Spatial pattern of significant explanatory variables of regression analysis in the CONUS. The map was created in ArcMap 10.8.1.

Table 2. Descriptive statistics and results of OLS and SER model of COVID-19 vaccination rates in the United States.

Domain	Variable	Minimum	Maximum	Average	Standard Deviation	Coefficient OLS	Coefficient SER	VIF
Social	% Republican voters	0	96.18	65.01	16.11	-0.507^{**}	-0.451^{**}	2.333
Social	% Population with college degree	0	60.32	15.74	6.90	0.229^{**}	0.260^{**}	1.855
Social	% Black population	0	87.45	8.80	14.16	-0.360^{**}	-0.343^{**}	1.570
Ecological	National Risk Index score	0	100	10.35	6.54	0.131^{**}	0.110^{**}	1.082
Technological	% Population with broadband access	0	100	65.45	31.18	0.020^{**}	0.024^{**}	1.254
Technological	Health facilities per 10 000 population	0	34.46	2.79	1.99	0.424^{**}	0.187^{*}	1.044
Spatial	Autoregressive coefficient					NA	0.478^{**}	
	AIC					22 768.2	22 238.4	
	R^2					0.476	0.585	

OLS = Ordinary Least Squares. SER = Spatial Error. VIF = Variation Inflation Factor. AIC = Akaike information criterion.
** indicates $p < 0.01$; * indicates $p < 0.05$.

also more likely to get vaccinated, and this trend is strong in many urbanized parts of the nation such as the Northeast (e.g. Maine, Pennsylvania, Virginias, Vermont), Midwest (e.g. Indiana, Michigan, Ohio, Dakotas), and the South (e.g. North Carolina, Florida), while populations with lower educational attainment show vaccine hesitancy in many counties of the relatively less urbanized counties in the South (e.g. Arkansas, Tennessee, North Carolina), the Southwest (e.g. California, Arizona), as well as the Mountain States (e.g. Montana, Wyoming).

Table 3. OLS (global) and GWR (local) coefficients of the empirical regression model.

	GWR					
	Minimum	Lower quartile	Median	Upper quartile	Maximum	OLS
Intercept	−65.41	63.14	69.00	89.55	215.24	77.95
% Republican voters	−1.96	−0.52	−0.43	0.24	0.93	−0.51
% Black population	−3.82	−0.34	−0.24	0.07	3.11	−0.36
% Population with college degree	−1.22	0.31	0.39	0.66	1.77	0.23
NRI score	−1.09	0.00	0.05	0.29	1.15	0.13
% Population with broadband access	−0.26	−0.02	0.01	0.06	0.40	0.02
Health facilities per capita (10k population)	−6.29	0.10	0.26	0.86	5.45	0.42
R^2	0.764					0.476
AICc	21 450					22 768.2
σ^2	50.46					88.72

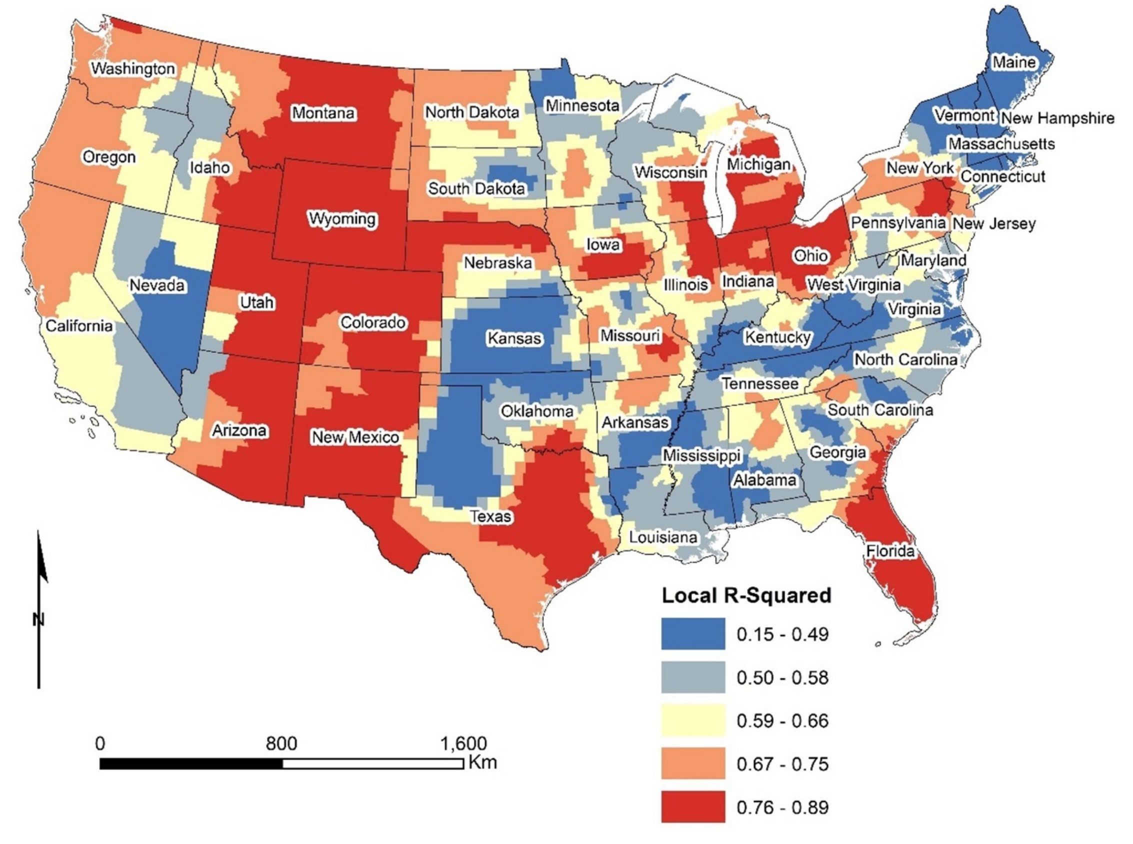

Figure 3. GWR model results of vaccination rates explained by the selected variables. The map was created in ArcMap 10.8.1.

For ecological indicators, only the NRI is statistically significant. Overall, the NRI is positively associated with vaccination rates. However, most US counties show insignificant relationships with this variable. Vaccine hesitancy is relatively stronger in parts of the Tornado alley region (e.g. Louisiana, Missouri), but weakens toward the interior west (e.g. Colorado, Nebraska, North Dakota). While vaccination rates are positively associated with NRI score in most counties, some counties do show negative associations with NRI scores (a portion of the midwest and poverty-belt along the Appalachian Mountains), indicating the potential role of public communication in these high ecological risk areas.

Two significant technological indicators play a part in vaccine hesitancy. Both are positively associated with vaccination rates. Populations with broadband access have a strong positive association with vaccination rates in much of the West (e.g. California, Oregon, Nevada) and in significant portion of the

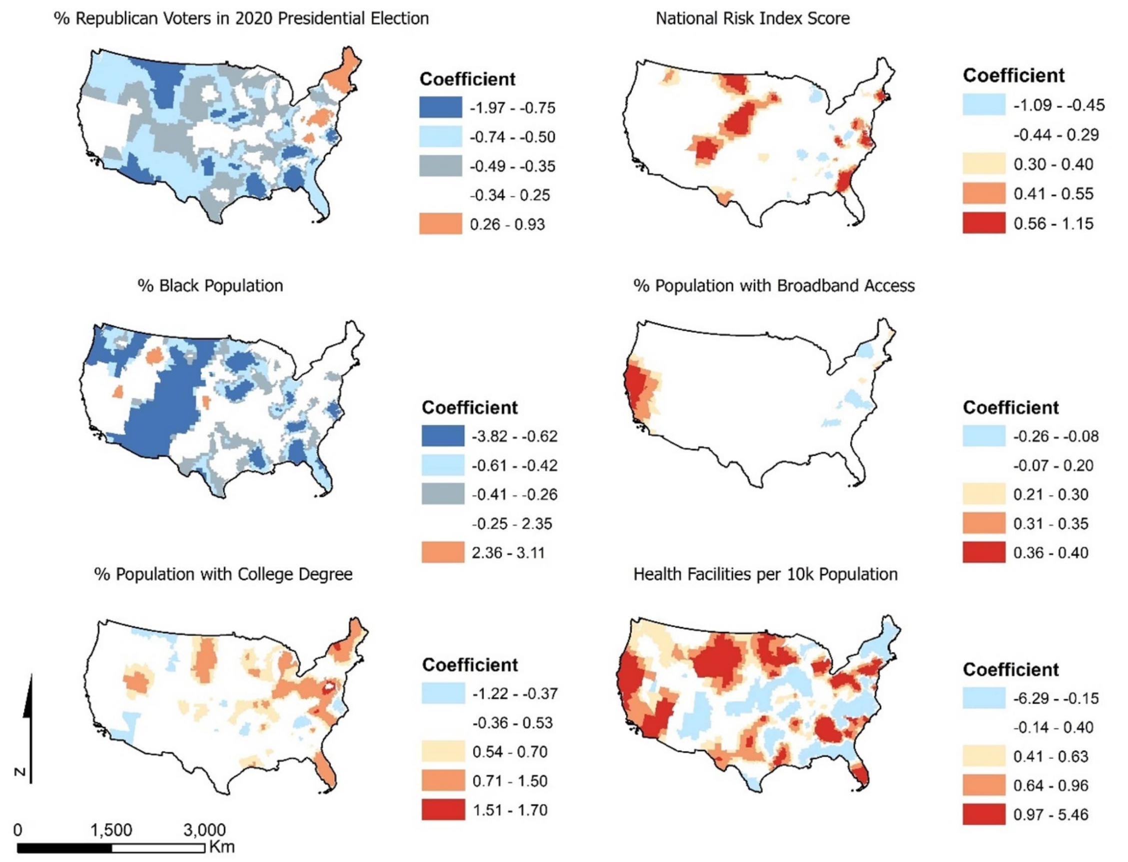

Figure 4. GWR model coefficient values showing statistically significant results. The map was created in ArcMap 10.8.1.

geographically smaller Rhode Island. However, populations with broadband access display negative association with vaccination rates in the American South (Georgia, North Carolina), as well as the Northeast (e.g. New York, Vermont), indicating that lack of or limited access to high-speed internet may have played a role in vaccine hesitancy there. Health facilities are also strongly linked to vaccination rates, especially along the Pacific Coast (Washington, Oregon, California) and Canadian border counties in the North (e.g. North Dakota, Minnesota). They are also positively linked to vaccination rates in many counties in the South (Alabama, Florida, Georgia). The lack of health facilities per capita population may have caused delays or loss of opportunity to vaccinate in some regions, especially in the Indian reservation territories (e.g. Arizona, Colorado, and New Mexico), as well as across the Plains (e.g. Kansas, Missouri, Iowa), and in parts of the South (e.g. Alabama, Florida, Georgia, North Carolina). Similarly, vaccine hesitancy linked to health facilities is also severe in many parts of the Northeast (e.g. New York, New Hampshire, Massachusetts, Maine, Vermont).

5. Discussion

Many COVID-19 outbreaks in US are currently attributed to those who do not agree with vaccines due to religious or political beliefs (Albrecht 2022). This vaccine hesitation can instill fear in even the most educated and intelligent citizens, causing a state of alarm. Many spatial patterns of vaccine hesitancy are fueled by misinformation spread by politicians, as shown by multiple studies (Allcott *et al* 2020, Evanega *et al* 2020, Shahi *et al* 2021). Allcott *et al* (2020) highlighted variations along political lines in social distancing, partisanship, COVID-19, and public policy. This explains the high vaccine hesitancy found among Republican voters in general, but this study found geographic variations in how vaccine hesitancy is spread even among Republican voters, particularly closer to the Canadian border in the west (e.g. Montana, Washington) and the Northeast (e.g. Maine, Vermont). The wide variation, while in part explained by factors such as religious beliefs (Scott *et al* 2021), political spectrum, and the like, does serve to highlight the potential for geographic patterns of vaccine hesitancy that could have policy implications and lead to improved communication. Indeed, studies have shown that efficient and consistent communication is key to changing people's minds on challenging public health issues, including medical treatments like vaccinations (Xantus *et al* 2021). At the same time, the low rates of vaccination among the Black population are fueled by a combination of lack of healthcare access or medical racism, as well as misinformation (Chee 2021, Savoia *et al* 2021, DiRago *et al* 2022). However, geographically, Black population vaccine hesitancy generally seems to vary with local political landscape, implying that varying factors–such as social-political context and healthcare access–may contribute to the observed differences in vaccination rates of the Black population. The findings imply that existing racial and spatial inequality in public health remains an issue (Kim and Kwan 2021, Pallathadka *et al* 2021). Our study additionally demonstrates that educated populations are less likely to be vaccine-hesitant, although this trend can vary geographically. Florida provides an interesting case, for example, where both Republican voters and the Black population are more hesitant of vaccines, but the college-educated population is more accepting of vaccines (figure 4). Spatial patterns can also be impacted by trust in government regardless of race and political affiliations (AlShurman *et al* 2021, Joshi *et al* 2021, Savoia *et al* 2021). Our finding of the NRI score in relation to vaccination highlights the importance of building trust in public communication and in government agencies. Indeed, studies have shown that the level of distrust in government influences people's willingness to vaccinate and or follow public communication (Park and Lee 2018, Joshi *et al* 2021, Offerdal *et al* 2021, Park *et al* 2021). Places with a high number of natural disasters are typically more familiar with government agencies and therefore less distrustful of them depending on the government response there. In the majority of the mountain states (e.g. Colorado, Wyoming), this seems to be the case where the disasters do not have maritime influence and government efforts here seem to be more successful. In contrast, places that have maritime influence with disasters such as hurricanes and sea-level rise still have low vaccination rates, implying the varying nature of public natural disaster mitigation efforts and outcomes. Beyond these factors, our findings emphasized that having reliable broadband internet access is essential for achieving high vaccination rates. Indeed, research via a national survey by Luo *et al* (2022) showed that respondents with internet access at home were more willing to get vaccinated. Berenbrok *et al* (2021) and Mohammadi *et al* (2021) suggested that access to healthcare is critical for high levels of vaccination, similar to our findings. Our results further suggest that health facilities per capita are strongly tied to urbanized counties, and this represents barriers to vaccination for rural counties that have a significantly lower proportion of adolescents vaccinated.

This analysis demonstrates the usefulness of a GWR model over OLS and SER models, especially in capturing the locally varying relationships between vaccination rate and explanatory variables. This study supports GWR (a local spatial analysis approach) over nonspatial global methods for explaining the spatial variation of vaccination rates. For example, the OLS model provided spatially stationary results, but GWR demonstrated the diversity of county-level vaccination rates to a much greater degree than OLS or SER. This finding should be considered by public health professionals and policymakers dealing with locally specific public health issues, especially those of a public disaster when analyzing spatially varying relationships.

Our models also demonstrate SETS as a useful framework in reviewing vaccine hesitancy. Other models that rely heavily on socioeconomic factors suffer from redundancy, and as such may benefit from using this expanded model that includes other ecological and technological factors. The results show the consideration of ecological and technological variables enrich the explanatory power of a regression analysis. After all, the SETS framework can be applied to any multilevel design, representing a basis for disentangling complex socioeconomic and geographic factors by aggregating them into variables. Public health policy analysts could use the findings of our information to understand the interactions among social, ecological, and technological variables. Overall, we believe that this framework can serve policymakers in developing critical decision-making tools.

There are some limitations to our study. The GWR model is exploratory in nature, thus it is not suitable for predicting vaccination rates independent of explanatory variables. Additionally, the vaccination rate is a continuously evolving number, and as such, many factors discussed in this study may change over time. The findings are shown at the county level, so interpretation at a different level is not recommended. We also recognize that certain sections of the population may have medical reasons (e.g. infants, immunocompromised individuals) not to vaccinate. Further, we acknowledge that variables used here may have substitutes that we could not capture in this study, which may have led to misspecification errors, particularly for those counties that exhibit lower R^2 values. Future research should explore these factors at a finer scale (e.g. Census Tract or Block Group) and investigate whether relationships remain the same. Additionally, different states and counties have implemented different policies related to COVID-19 mitigation. Thus, future research is warranted to examine how different policies affect vaccination rates.

6. Conclusions

Public health experts have repeatedly stressed that achieving universal vaccination is key to controlling the incidence of vaccine-preventable diseases such as COVID-19. In this study, we explored factors explaining vaccination rates to understand vaccine hesitancy from a comprehensive SETS lens. Our research highlighted that socio-political, environmental, and technological determinant of vaccine hesitancy might vary across regions. We found six statistically significant predictors; two variables, % Republican voters and % Black population were negatively correlated with the vaccination rates, whereas four remaining variables, % Population with college degree, NRI Score, % Population with broadband access, and Health facilities per 10,000 population were positively correlated with the vaccination rates at the county level. The relationships were varying geographically, with clusters of local hotspots spread across the CONUS. Highly focused government intervention through consistent communication, well-structured immunization schedules, and feedback on vaccination status may help foster vaccine hesitancy mitigation where it exists. While a pragmatic approach to dealing with vaccination hesitancy in the interest of greater public health is a lesson from our study, we also recommend ongoing observation and documenting these local dynamics to monitor and better understand vaccine hesitancy and how to mitigate it.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Acknowledgments

This research was supported by the Urban Resilience to Extremes Sustainability Research Network under Award Number SES-1444755. We would to like thank Professor Inmaculada Hernandez (UCSD) for kindly sharing the health facilities summary data. We also benefitted from the resources of the WISE Lab at Portland State University. We thank Professor Idowu Ajibade and members of PEARL Lab at Portland State University for their feedback. We also thank the three anonymous reviewers for their many insightful comments and suggestions.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Arun Pallathadka conceived the study, designed the study and data-analysis, obtained data, conducted data-analysis, interpreted results, wrote a draft of the manuscript, and edited the manuscript. Heejun Chang supervised the study, designed the study and data-analysis, reviewed data-analysis, interpreted results, wrote a draft of the manuscript, and edited the manuscript. Daikwon Han reviewed data-analysis, interpreted results, and edited the manuscript.

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