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Research Report

# Can vaccine prioritization reduce disparities in COVID-19 burden for historically marginalized populations?

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## Abstract

SARS-CoV-2 vaccination strategies were designed to reduce COVID-19 mortality, morbidity, and health inequities. To assess the impact of vaccination strategies on disparities in COVID-19 burden among historically marginalized populations (HMPs), e.g. Black race and Hispanic ethnicity, we used an agent-based simulation model, populated with census-tract data from North Carolina. We projected COVID-19 deaths, hospitalizations, and cases from 2020 July 1 to 2021 December 31, and estimated racial/ethnic disparities in COVID-19 outcomes. We modeled 2-stage vaccination prioritization scenarios applied to sub-groups including essential workers, older adults (65+), adults with high-risk health conditions, HMPs, or people in low-income tracts. Additionally, we estimated the effects of maximal uptake (100% for HMP vs. 100% for everyone), and distribution to only susceptible people. We found strategies prioritizing essential workers, then older adults led to the largest mortality and case reductions compared to no prioritization. Under baseline uptake scenarios, the age-adjusted mortality for HMPs was higher (e.g. 33.3%–34.1% higher for the Black population and 13.3%–17.0% for the Hispanic population) compared to the White population. The burden on HMPs decreased only when uptake was increased to 100% in HMPs; however, the Black population still had the highest relative mortality rate even when targeted distribution strategies were employed. If prioritization schemes were not paired with increased uptake in HMPs, disparities did not improve. The vaccination strategies publicly outlined were insufficient, exacerbating disparities between racial and ethnic groups. Strategies targeted to increase vaccine uptake among HMPs are needed to ensure equitable distribution and minimize disparities in outcomes.

**Keywords:** vaccine equity, health disparities, COVID-19, agent base simulation

### Significance Statement:

Although equity was one of the tenets of vaccine distribution, this study suggests that targeted vaccination strategies that surpass current vaccination policy must be implemented to reduce inequity faced by historically marginalized populations. Public health policy must consider health inequities when developing and implementing vaccination strategies for booster shot distribution and response to this and future pandemics.

## Introduction

Throughout the COVID-19 pandemic, historically marginalized communities of color have experienced a disproportionate burden of morbidity and mortality (1–7). The unequal impact on these populations is driven by risk factors such as essential-worker status, age, living arrangements, and high-risk medical conditions (1, 2, 4–6). In response, the National Academies of Sciences, Engineering, and Medicine (NASEM) (7) drafted a framework for the equitable allocation of SARS-CoV-2 vaccines, which aimed at overall reductions in morbidity and mortality and explicitly outlined approaches to mitigate structural inequities. Despite this guidance, there was substantial variability in vaccine rollout strategies at the state and local levels. All the states included healthcare workers and long-term care facility residents in their initial priority groups, but subsequent phases included prioritization for varying combinations and orderings of groups such as

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frontline essential workers, educators, congregate living facility residents and staff, those with high-risk medical conditions, and older populations (8). Which strategies best achieved the goals set out by the NASEM or what approaches will most effectively accomplish future public health targets aiming to reduce disparities remains unknown.

Vaccination prioritization scenarios have been studied using various modeling approaches (9–12). The findings suggested that prioritizing older adults had the greatest impact on COVID-19 mortality, while prioritizing individuals who have a large number of interactions with other individuals during the day had the greatest impact in reducing morbidity (e.g. incidence of disease) (9, 10). Fujimoto et al. (12) studied susceptible-only distribution (i.e. distributing vaccines only to people without a previous case of COVID-19) and found it to be effective for increasing the benefit of COVID-19 vaccine supply. Ferranna et al. (10) assessed equity by assuming essential workers in their model are more likely to be members of vulnerable populations. They reported that prioritizing older adults over vulnerable populations led to higher reduction in mortality; however, they did not explicitly consider racial and ethnic disparities that may arise under different vaccination scenarios. To our knowledge, no studies have explicitly designed or tested vaccination strategies explicitly considering race and ethnicity in the models, nor tested additional vaccination strategies aimed at increasing uptake within population subgroups.

Vaccine equity discussions and efforts focused on reducing health inequities that are related to systemic social injustices, e.g. targeting those at disproportionate risk for COVID-19 (13) through measures such as identifying zip codes based on incidence rates or disadvantage indices (14) (e.g. social vulnerability index). Some have warned that prioritizing adults aged 65+ without working to remove barriers and promote equity could worsen existing racial disparities (15). Reitsma et al. (6) concluded that equity-focused public policy is required to address disparities that have arisen during the pandemic. These studies highlighted the need for equity-focused modeling that explicitly captures the racial and ethnic demographics of the population, multigenerational households, demographic-informed workplace activity throughout the pandemic, and vaccine uptake as a function of racial/ethnic and age characteristics of the population.

We developed a COVID-19 transmission and disease progression model, populated with data from North Carolina, to compare vaccination prioritization strategies by total infections and severe outcomes with an emphasis on quantifying/assessing/measuring racial and ethnic disparities of historically marginalized populations (HMPs). Here, HMPs are composed of Black (non-Hispanic Black), other (non-Hispanic Asian, American Indian or Alaska Native, Native Hawaiian or other Pacific Islander, other race, or multiracial), and Hispanic (White Hispanic, Black Hispanic, and other Hispanic). Most existing models (9–12) do not account for race/ethnicity directly, and thus, can not estimate disparities in COVID-19 outcomes. Our simulation captures systemic factors by race and ethnicity through model input data and agent behavior. We consider not only differences in age and household size distributions by race/ethnicity but other factors that influence infectivity and severity of the disease such as essential worker status, presence of a high-risk medical condition, and workforce mobility. In this analysis, we focused primarily on the first 6 months of vaccine rollout in the USA, when availability was limited. We evaluated prioritization strategies based on age (e.g. 65+), type of employment (e.g. nonmedical essential workers), health risks (e.g. people with chronic conditions such as diabetes), and social vulnerability (e.g. HMPs). We also explored operational strategies such as susceptible-only distribution and strategies that increased uptake (e.g. achievable through strategies that reduced barriers to access, built trust, or increased communication (13, 15, 16)). This analysis demonstrates the importance of accounting for systemic factors that vary by race/ethnicity when evaluating policy outcomes, indicating equity needs to be at the forefront of current and future vaccination policy.

# Methods

## Model structure

We developed an agent-based extended Susceptible-Exposed-Infected-Recovered (SEIR) simulation model with an embedded network structure where agents interact in households, peer groups such as workplaces or schools, and the community (Figures S1, S2, and S9, Supplementary Material). We modeled the population of North Carolina using a ∼1:10 proportional representation of 1,017,720 agents. Census tract-level data (17) was used to assign the distribution of individuals by race, ethnicity, age, and households of different sizes. Each agent is in one of (i) 5 age groups: children (0–4, 5–9, and 10–18), adults (19–64), and older adults (65+), and (ii) 4 race/ethnicity groups: White (non-Hispanic White), Black (non-Hispanic Black), other (non-Hispanic Asian, American Indian or Alaska Native, Native Hawaiian or other Pacific Islander, other race, or multiracial), and Hispanic (White Hispanic, Black Hispanic, and other Hispanic). HMPs included Black, Hispanic, and other. We incorporated SafeGraph mobility data at the census tract level (Figure S3, Supplementary Material), where we assumed essential workers were those working full-time away from home in January 2021 (18). Essential worker assignment by race and ethnicity was assigned according to the national distribution since state-level data were not available (19), which had a higher rate for non-whites (Figure S4, Supplementary Material). We illustrate the effect of high risk conditions by incorporating diabetes, which corresponds to increased risk of hospitalization (20); with agent assignment based on the state-level prevalence specific to agents' age and racial/ethnic group (21). We modeled nonpharmaceutical interventions (NPIs) including face mask use and limited mobility over time (Figure 1). Using the model, we projected the disease spread for approximately 18 months, accounting for the Alpha variant strain's spread in North Carolina. We compared various equity-driven vaccination prioritization strategies using outcome metrics of cumulative infections, hospitalizations, and deaths, and we assessed disparities using the age-adjusted differences of each outcome (with respect to the population of North Carolina) for each HMP relative to the White population. We include the age-specific mortality rates (22) in Figures S23–S25 (Supplementary Material), and estimate differences in years of life lost per 100,000 (9) in Figures S15 and S16 (Supplementary Material) as additional output metrics in the supplement using the data shown in Figures S7 and S8 (Supplementary Material).

## Vaccination prioritization and distribution scenarios

We modeled 29 vaccination-prioritization and distribution scenarios (Figures S17–S19, Supplementary Material) considering a combination of (i) target vaccination groups, (ii) vaccine uptake, and (iii) susceptible-only distribution. A total of 8 million doses were distributed at a uniform daily rate from 2021 January 10 until 2021 August 24. Vaccinations were administered to the 75+

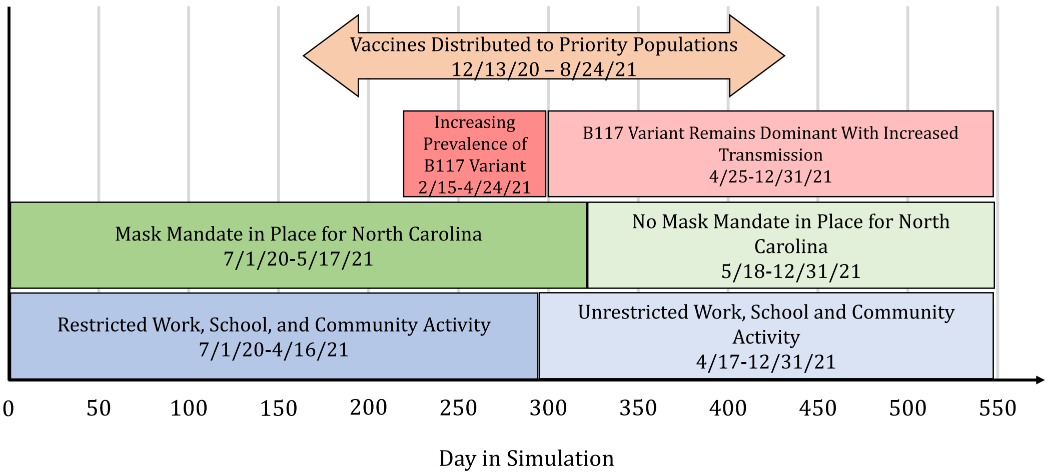


**Fig. 1.** Simulation timeline for NPI, variant, and vaccine behavior. Source: agent-based simulation model timeline regarding NPIs, mobility, variants, and vaccination.

and frontline populations beginning on 2020 December 13. In each scenario, the first-dose distribution targeted a specific group until either 60% of the prioritized group had been vaccinated or uptake had been fully satisfied, whichever occurred first, before extending eligibility to the next group, per CDC guidance (23). We assumed agents were eligible for a second dose 28 days after the first dose, with 15% attrition (24). Vaccine efficacy occurred 2 weeks after a dose (70% after the first and 90% after the second). Vaccination implementation details can be found in Figure S10 (Supplementary Material).

*Priority population combinations and ordering scenarios:* the groups studied were people age 65+ (Age), adults with a high-risk condition, essential workers (Essential), HMPs, those that live in a low-income census tract, and the adult population for which there is no prioritization. Ordering scenarios consisted of 2 groups. After the second group was vaccinated, eligibility opened to all the remaining adults. Here, we focused on the Age and Essential priority groups which correspond to Age–Essential (Group 1: Age and Group 2: Essential) and the Essential–Age (Group 1: Essential and Group 2: Age) prioritization orderings. The baseline scenario for this study was the Age–Essential (25).

*Vaccine uptake:* the *baseline* vaccine uptake parameter captures a combination of an agent's hesitancy to vaccinate and access to the limited supply (e.g. location/transportation accessibility, language barriers, ease of appointment scheduling, and so on). Baseline vaccine uptake followed historical uptake trends from seasonal flu vaccine coverage (26). For age 65+, the uptake was 71.9%, 62.3%, 59.3%, and 71.9%, for White, Black, Hispanic, and others, respectively. The corresponding uptake for ages 20–64 was 45%, 36.7%, 36.1%, and 45%, respectively. Figures S20–S22 (Supplementary Material) show simulation uptake.

Additional scenarios included increasing uptake to 100% for (i) HMPs and (ii) everyone. While 100% uptake may be unlikely in practice, this extreme scenario provided insightful results by establishing an upper bound for comparison. Since we assumed limited supply, most populations would not be fully vaccinated even under scenarios with 100% uptake.

*Susceptible-only distribution:* under the susceptible-only distribution strategy, doses are only given to susceptible agents. Operationally, this is comparable to administering an antibody test immediately prior to vaccination and only vaccinating individuals without antibodies. This maximizes the utility of the vaccine by leveraging the natural immunity of those previously infected (12).

### Validation

The model has been used previously to answer questions regarding the impact of masks, school closures, testing strategies, and lifting of NPIs before full vaccination (27–32). We validated our model on cumulative lab-reported infections, hospitalizations, and deaths through 2021 April 15, for the total population and subpopulations stratified by race/ethnicity or age, using estimates of lab-reported infections as described in Figures S11 and S12 (Supplementary Material).

## Results

*Baseline:* at the time when vaccine distribution was assumed to begin, the simulated cumulative percentage of the population infected was approximately 18.6% with Black, Hispanic, other, and White having 21%, 20.2%, 20.8%, and 17.6% age-adjusted infection rates, respectively. In the baseline vaccination prioritization scenario, we found the following simulated outcomes by 2021 December 31, at the state level: cumulative infections of 42.9%, 796 hospitalizations per 100,000, and 174 deaths per 100,000. This corresponded to the following outcomes for Black, Hispanic, other, and White: 45.8%, 46.3%, 44.6%, and 42.4% age-adjusted infection rate; 838, 779, 748, and 691 age-adjusted hospitalizations per 100,000; and 181, 158, 152, and 135 age-adjusted hospitalizations per 100,000, respectively.

### Effect of prioritization and ordering

At the state level, as shown in Figure 2(a), the Age and Essential prioritizations led to a significant reduction in deaths (2.5% or 460 deaths) compared to no prioritization. Prioritizing Essential–Age significantly reduced infections (4.2%) compared to prioritizing Age–Essential, without significantly impacting the death rate. At the subpopulation level, Age–Essential prioritization reduced the White population's death rate by 2.6% compared to no prioritization (Figure 2b vs. d), but did not significantly reduce morbidity or mortality for any HMPs. Under Age–Essential prioritization (Figure 2c), greater morbidity and mortality continued for HMPs

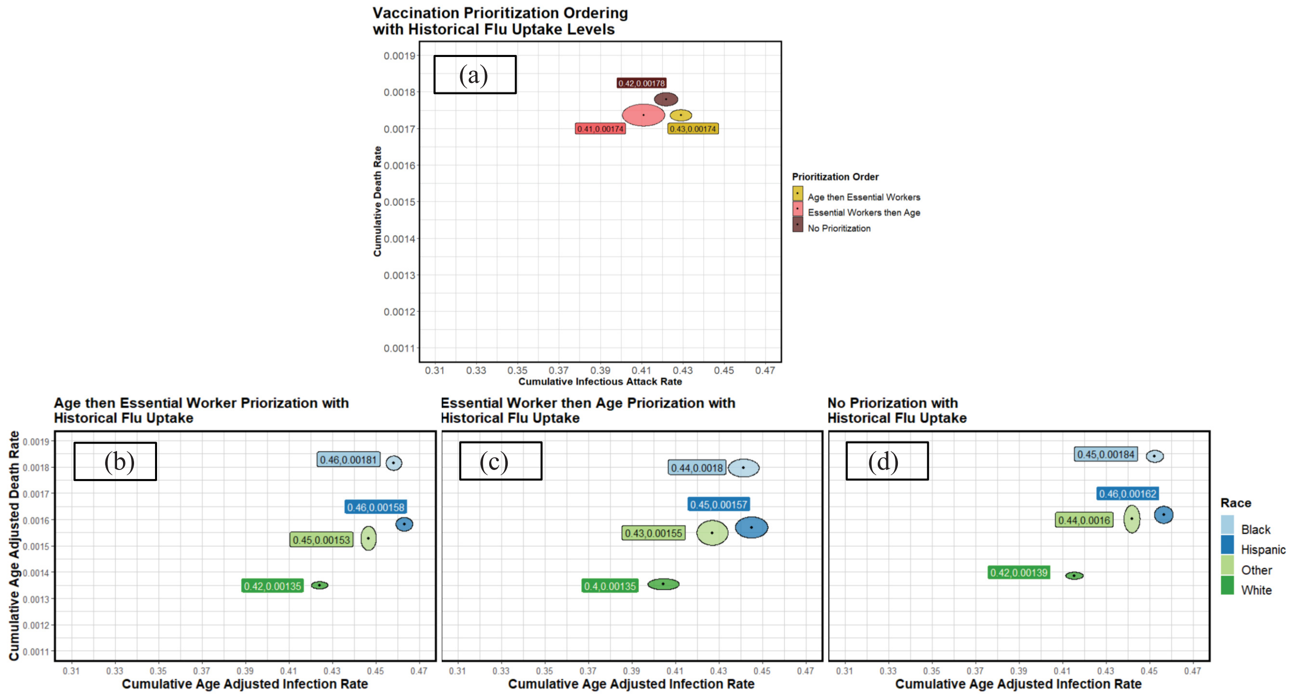


**Fig. 2.** Impact of prioritization under historical flu vaccine uptake at the state and subpopulation levels. Panel (a) provides state level results, and panels (b)–(d) provide results stratified by race/ethnicity. Source: data shown are generated from the agent-based simulation model across 45 replications. Notes: each panel shows the average age-adjusted infection attack rate (x-axis) and the average age-adjusted death rate (y-axis) with 95% confidence intervals represented with ovals, with scales consistent across all similar figures.

compared to the White population, 8.1%, 9.2%, and 5.3% more infections and 34.4%, 17.1%, and 13.2% more deaths for Black, Hispanic, and other populations, respectively.

A total of 6 additional prioritization scenarios are shown in Figure S17 (Supplementary Material). Among the scenarios, Essential–Age reduced morbidity the most for the state level population and at the subpopulation level. Age–Essential and Essential–Age reduced mortality the most for the state level population and at the subpopulation level with historical flu vaccine uptake.

## Effect of vaccine uptake and susceptible-only vaccination on outcomes

At the state level (Figure 3a), increased uptake in the HMPs reduced deaths by 2.6% or 472 deaths prevented and did not significantly increase the infection rate compared to baseline uptake. At subpopulation level, we saw that increased uptake corresponded to significant reductions in both morbidity and mortality for the Black, Hispanic, and other populations: 9.4%, 8.9%, and 6.7% reduction infections and 18.9%, 17.8%, and 12.5% reduction in deaths, respectively (Figure 3c). Compared to the White population, the Black, Hispanic, and other populations had 9.3%, 7.9%, and 9.0% fewer infections. Despite the reduced infection rate, the Black population had 2% more deaths while the Hispanic and other populations had 9.8% and 7.2% fewer deaths under the increased uptake scenario compared to the White population.

Figure 3(a) shows that susceptible-only distribution could lead to additional reduction in morbidity and mortality, at the state level, and for each subpopulation. There was a 4.6% and 3.8% reduction in infections and deaths, respectively, relative to the historical flu vaccine uptake scenario. At the subpopulation level, Figure 3(d) shows that susceptible-only distribution led to a significant reduction in morbidity for the Black, Hispanic, other, and White populations: 3.5%, 4.2%, 3.9%, and 5.1%, respectively, and a significant reduction in mortality for the Black and White populations 4.0% and 4.2%, respectively. For Age–Essential, there was no reduction of disparities associated with susceptible-only distribution alone.

When susceptible-only distribution and increased uptake in HMPs were operationalized simultaneously, the greatest reduction of morbidity and mortality relative to the baseline scenario was observed. At the state level, there was a 13.8% and 14.1% reduction in infections and deaths, respectively (Figure 3a). By subpopulation, the Black, Hispanic, other, and White populations' morbidity and mortality were reduced by 25.4%, 25.7%, 22.8%, and 13.1% and 25.2%, 27.2%, 21.1%, and 7.6%, respectively (Figure 3e). Despite the large reductions, the Black population continued to have the highest death rate.

Results for 16 other scenarios are in Figures S18 and S19 (Supplementary Material).

Figure 4 shows the equity gap pre and postvaccine administration. Under vaccination prioritization scenarios without increased uptake in HMPs, the equity gap increased significantly relative to the prevaccine values. When uptake is increased to 100% in HMPs, the Hispanic and other populations achieved lower death rates than the White population. However, the Black population still faced significant disparities in the age-adjusted death rate relative to the White population under all scenarios. Figures S13 and S14 (Supplementary Material) show the corresponding graphs for cumulative age-adjusted infection and hospitalization rates, respectively. Additionally, Figures S15 and S16 (Supplementary Material) show estimates of the difference in years of life lost rate per 100,000 by age group and race/ethnicity as an additional quantification of disparities.

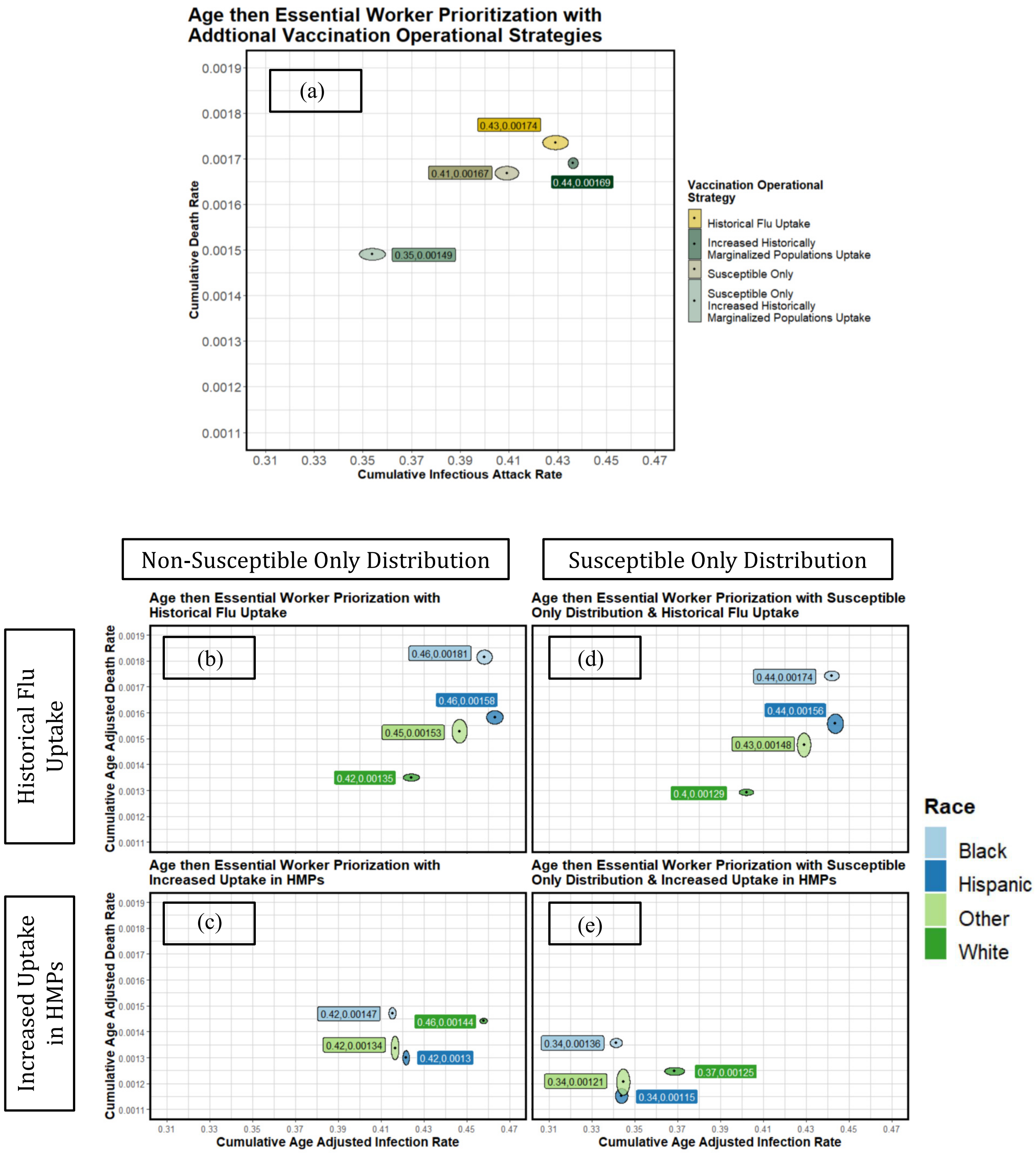


**Fig. 3.** Impact of vaccine uptake and susceptible-only distribution at the state and subpopulation levels. Panel (a) provides state level results, and panels (b)–(e) provide results stratified by race/ethnicity. Source: data shown are generated from the agent-based simulation model across 45 replications. Notes: each panel shows the average age-adjusted infection attack rate (x-axis) and the average age-adjusted death rate (y-axis) with 95% confidence intervals represented with ovals, with scales consistent across all similar figures.

## Discussion

Using a simulation-based model, we compared several COVID-19 vaccination strategies. We found that prioritization schemes that did not incorporate increased uptake in HMPs did not reduce disparities and may further exacerbate prevaccine disparities. For infections, hospitalizations, and deaths, the results showed an increased age-adjusted equity gap for HMPs, unless there is increased uptake. At the extreme, we found that, even with universal uptake, the Black population continued to have a higher post-vaccine death rate than the White population. Although equity was one of the tenets of vaccine distribution (4, 23, 25), the current distribution strategy outlined by federal agencies is insufficient to reduce disparities between racial and ethnic groups that existed prevaccination.

Disparities in COVID-19 outcomes may persist and even worsen in HMPs due to systemic biases that increase the risk of infection and severe disease and lower historical uptake (1–3, 5, 6, 33), some of which were captured in our model. HMPs face greater workplace exposure due to their disproportionate essential worker status in the model (Figure S4, Supplementary Material) (19). The Hispanic population has larger average household sizes (Figure S5,

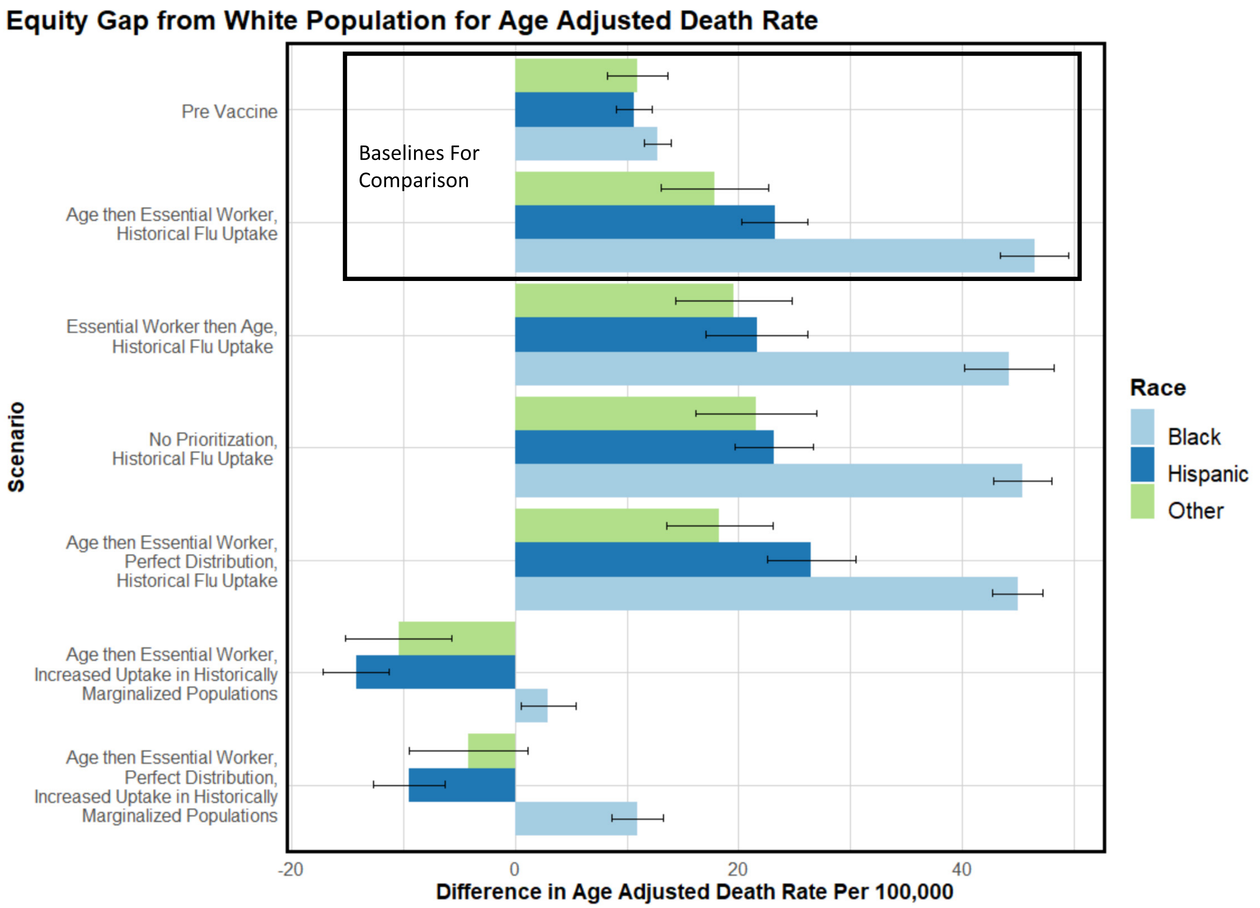


**Fig. 4.** Equity gap from the White population for each HMP by vaccination scenario. Source: data shown are generated from the agent-based simulation model across 45 replications. Notes: equity gap is defined as the difference in cumulative age-adjusted death rates between the White and each HMP. The y-axis indicates the vaccination scenario. Figure contains the corresponding 95% confidence intervals.

Supplementary Material) (17), and the Hispanic and Black populations have a younger average population (Figure S5, Supplementary Material) (17). These factors correspond to more interactions in the model. The Black population has a higher rate of diabetes for both 20–64 and 65+ adults (Figure S6, Supplementary Material) (21). The diabetes rate in combination with essential-worker mobility, contributes to the high death rates relative to other populations and the equity gap observed prevaccination (Figure 4). When risk factors are coupled with lower historical uptake (26) and biases that result from age prioritization in a population where Whites comprise the majority of the older population (17), HMPs may face increasing disparities (Figure 4). In addition to these risk factors, others such as systemic racism likely exacerbate disparities in morbidity and mortality.

Our findings are consistent with the previous studies that show prioritizing the older adult population is important for reducing mortality at the state level (6, 9, 10). Further, our study suggests increasing uptake in HMPs is critical for reducing disparities in COVID-19 morbidity and mortality. Under constrained supply, our model shows that leveraging natural immunity through susceptible-only distribution is critical to have in combination with increased uptake to reduce morbidity and mortality for all subpopulations. These operational vaccination strategies would not have required additional vaccine supply, yet they could have averted 830K infections and 2,700 deaths compared to the baseline. Such strategies, however, might require additional laboratory infrastructure to confirm existing immunity, which may not be feasible, especially in rural and resource-limited areas. To improve uptake, both access and vaccine hesitancy must be addressed with equity-focused public health policy (6, 13, 34, 35). This could take the form of mobile vaccine clinics, removing barriers to appointment-scheduling or registration, providing multilingual communication on registration and vaccine safety, extended operational hours, paid time off, or travel expense compensation (4, 35–39). Additional approaches could include interpersonal communication with healthcare professionals that focus on personal benefits of receiving a vaccine and working to dispel misinformation regarding the vaccine's safety and efficacy (34, 40, 41). The challenge of reducing disparities is made more difficult by the fact that there is incomplete data (e.g. limited breakdown by characteristics like race/ethnicity) across the nation on who has had COVID-19 and who has been vaccinated. Collecting data on race/ethnicity systematically across the USA should be encouraged during national emergencies and in other health applications, to monitor inequities and inform efforts to reduce them.

Significant equity gaps existed for HMPs prior to vaccine rollout. Equity-focused public health policy needs to extend beyond the scope of the pandemic to address the root causes of these disparities. These include ensuring equitable access to healthcare resources and taking action to reduce the prevalence of high-risk conditions such as diabetes. Establishing more equitable public health policies now will better protect vulnerable populations in the future, as uncertainty remains due to the emergence of new and potentially more infectious variants of SARS-CoV-2 (42, 43). Equitable policy is particularly important when planning for current and future vaccination challenges. Potential booster shots and newly eligible vaccination age groups require equity as a key component, as access barriers will further increase morbidity and mortality within historically marginalized communities of color and communities with low uptake. This analysis can also inform the current COVID-19 vaccine rollout in other countries and for future pandemics by presenting effective vaccine prioritization strategies and demonstrating vaccine prioritization's impact on equity and the critical role policymakers hold. Vaccine distribution policy must take explicit action to ensure prior disparities in vaccination are not repeated by increasing uptake in HMPs.

### Limitations

Model validation was conducted independently for age, race, and ethnicity rather than at the intersection of the 3 attributes due to data availability limitations. Validation shows the model underestimated disease burden within the Hispanic community. This is due, in part, to data limitations surrounding the migrant worker population. As a low estimate, 150,000 migrant farm workers come to North Carolina each growing season, with 94% being native Spanish speakers (44). Nationally, 53% of migrant workers are undocumented, which leads to underreporting in census data (43) and leads to a misrepresentation of the population within the simulation. The age bracket definitions are also a limitation within the model. For the adult population, we are not able to capture the workplace mobility or community interaction differences. This also limits the assignment of diabetes within the population. The older adult population does not have a workplace peer group, which limits our ability to capture disease spread and the racial/ethnic and comorbidity-based disparities that arise in this population. Similarly, the other racial/ethnic group contains multiple subpopulations that do not have the same behaviors or health profiles, which limits our ability to quantify their disparities. We only illustrate the effect of high-risk chronic conditions within the population with diabetes which does not capture their full impact. The variant is modeled by increasing the transmissibility of the disease, rather than introducing a competing strain into the population. This implementation may overestimate the impact of the variant on disease spread. Additionally, there is limited understanding of the variant's prevalence in the population, as genomic surveillance in North Carolina is limited (45). While we do not explicitly analyze the Delta variant, an increase in transmissibility with similar case fatality rates would be expected to exacerbate the disparities modeled herein. Finally, we assume masking ends on a particular date whereas in reality, people may continue to wear masks voluntarily and through workplace or school mandates. As a result, our model may overestimate infections (Figure S11, Supplementary Material).

### Conclusions

Our analysis suggests that the racial and ethnic disparities in COVID-19 morbidity and mortality that existed before the availability of effective vaccines could be exacerbated by vaccination prioritization strategies that do not directly increase uptake within HMPs. Across all scenarios, we found that prioritizing older adults had the greatest impact on reducing mortality, while prioritizing essential workers had the greatest impact on reducing morbidity. Disparities in disease burden could only be reduced through targeted strategies to increase uptake. It is critical to consider public health policies that emphasize equity in planning for vaccine boosters and mass vaccination strategies for future pandemics.

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## Supplementary Material

Supplementary material is available at *PNAS Nexus* online.

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## Author Contributions

J.S.I., M.M., and J.L.S. had full access to all the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis.

*Concept and design:* E.T.R., J.S.I., M.E.M., and J.L.S.

*Acquisition, analysis, or interpretation of data:* E.T.R., J.M., J.S.I., M.E.M., M.D.P., K.H.L, K.J., P.D., R.B., R.S., and J.L.S.

*Drafting of the manuscript:* E.T.R., J.M., J.S.I., M.E.M., R.B., and J.L.S.

*Critical revision of the manuscript for important intellectual content:* E.T.R., J.M., J.S.I., M.E.M., M.D.P., K.H.L., K.J., P.D., P.K., R.B., R.S., and J.L.S.

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*Supervision:* J.S.I., M.E.M., M.D.P., K.H.L., P.K., and J.L.S.

## Data Availability

The data that supports the findings of this study are available from the corresponding author, J.L.S., upon reasonable request.

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