



Historical Redlining and Resident Exposure to COVID-19: A Study of New York City

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Abstract

The Coronavirus Disease 2019 (COVID-19) has been reported to disproportionately impact racial/ethnic minorities in the USA, both in terms of infections and deaths. This racial disparity in the COVID-19 outcomes may result from the segregation of minorities in neighborhoods with health-compromising conditions. We, thus, anticipate that neighborhoods would be especially vulnerable to COVID-19 if they are of present-day economic and racial disadvantage and were redlined historically. To test this expectation, we examined the change of both confirmed COVID-19 cases and deaths from April to July, 2020, in zip code tabulation areas (ZCTAs) in the New York City using multilevel regression analysis. The results indicate that ZCTAs with a higher proportion of black and Hispanic populations are associated with a higher percentage of COVID-19 infection. Historically low-graded neighborhoods show a higher risk for COVID-19 infection, even for ZCTAs with present-day economic and racial privilege. These associations change over time as the pandemic unfolds. Racial/ethnic minorities are bearing the brunt of the COVID-19 pandemic's health impact. The current evidence shows that the pre-existing social structure in the form of racial residential segregation could be partially responsible for the disparities observed, highlighting an urgent need to stress historical segregation and to build a less segregated and more equal society.

Keywords COVID-19 infection and death · Racial disparities · Redlining · Residential segregation

Introduction

In the ongoing battle against the Coronavirus Disease 2019 (COVID-19), deadly racial disparities have emerged as a concern, drawing academic and public attention. It has been widely reported that COVID-19 is disproportionately impacting black and Hispanic communities in the USA, both in terms of infections and death. These reports have been substantiated by emerging research (Bertocchi & Dimico, 2020; Laurencin & McClinton, 2020; Lieberman-Cribbin et al., 2020; Yu et al., 2020). The disparity is especially prominent in New York City (NYC), which was the epicenter of the coronavirus crisis in the USA in March, 2020. There have been at least 254,023 cases of coronavirus and at

least 23,879 deaths in NYC as of October 10, 2020, according to the John Hopkins University & Medicine Coronavirus Resource Center. The distribution of confirmed positive cases are not homogeneous in NYC. Neighborhoods with the high concentrations of black and Latino populations arguably bear the brunt of the COVID-19 pandemic. For instance, the death rate in the 11239 zip code—a community in southeast Brooklyn home to many African American residents—was the NYC's highest as of May, 2020, and almost two times the death rate in the 10029 zip code in East Harlem, a predominantly white neighborhood (Schwartz, 2020).

A few studies have indicated that the segregation of blacks and Hispanics in neighborhoods afflicted with poverty and accompanied by health-compromising conditions may contribute to racial disparities in COVID-19 (Bertocchi & Dimico, 2020; Laurencin & McClinton, 2020; Lieberman-Cribbin et al., 2020; Yu et al., 2020). The current segregation pattern reveals spatial distributions of racial groups, but does not directly measure the underlying processes that created and sustained the pattern. Recently, studies have confirmed relationships between discriminative historical practices, such as housing discrimination in the form of redlining, and

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health status, including self-rated health (McClure et al., 2019), asthma (Nardone, et al., 2020a, 2020b), and preterm birth rate (Matoba et al., 2019). However, studies have been slow to investigate the relationship between patterns of discriminative historical practices and COVID-19. COVID-19, as a contagious disease, could spread with an unprecedented rate in residential areas, highlighting the urgency to probe the role of racial residential segregation in elevating or reducing the risk of COVID-19. In this paper, we examine relationships between racial residential segregation (both current and historic) and COVID-19 using data from April to July, 2020, in NYC, contributing to a growing body of work examining racism, segregation, and health.

Literature Review

Racial residential segregation refers to the spatial separation of population along the racial line (Popescu et al., 2018). In a segregated society, racial minorities tend to live in different neighborhoods than whites. Racial residential segregation has been long entrenched in American society. In year 2010, an average white people in a metropolitan area lived in a neighborhood that was 75% white and 8% black, whereas on an average black people lived in a neighborhood that was 45% black and 35% white (Phelan & Link, 2015). The relationship between racial residential segregation and health has been well studied and recognized. Residing in poor and segregated neighborhoods has been linked to poor health and mortality (Bruce et al., 2009; Kawachi & Berkman, 2003). Williams and Collins (2001) regarded racial residential segregation as a fundamental cause of racial disparities in health. Furthermore, Phelan and Link (2015) identified racism as a fundamental cause of socioeconomic-related resources, which in turn are the fundamental cause of health outcomes. Following this logic, racial residential segregation, as a manifestation of racism, its importance in understanding racial differences in health is hard to overstate. The mechanism through which racial residential segregation impacts health outcomes are multi-dimensional. Racial residential segregation is associated with one's educational attainment, jobs, wealth accumulation (e.g., housing) through determining the neighborhood that one lives. Desirable neighborhoods bundle together beneficial sets of circumstances that promote health directly and indirectly. On the contrary, undesirable neighborhoods tend to expose residents to health-compromising conditions. Firstly, neighborhoods influence the collective resources, such as the availability, accessibility, and affordability of schools, healthy foods, parks, and medical care (Phelan & Link, 2015). In this sense, health-compromising neighborhood conditions include, but not limited to, an abundance of unhealthy food, a vacuum of healthcare resources, and proximity to

pollutants. Secondly, neighborhoods also offer beneficial social ties. For instance, neighbors with rich socioeconomic resources are more likely to provide beneficial connections for college admission and job procurement (Phelan & Link, 2015).

Across a variety of cities and districts, researchers have found significant racial disparity in the confirmed cases and deaths of COVID-19. Several studies showed that the segregation of black and Hispanic neighborhoods in American cities predicted a marked increase in the rate of the growth of both confirmed COVID-19 cases and deaths (Laurencin & McClinton, 2020; Lieberman-Cribbin et al., 2020; Yang et al., 2020; Yu et al., 2020; Zhang & Schwartz, 2020). These studies on COVID-19 used county as the aggregate level. The understanding of the COVID-19 at national and state scales is undoubtedly important; however, understanding its dynamics at a finer level is of equal importance, for the reason that a locational component study scale could have a nontrivial impact on the outcome (Maroko et al., 2020). However, only handful studies used smaller geographic units, such as metropolitan areas. Among these, a few investigated the racial inequality if COVID-19 in NYC (Lieberman-Cribbin et al., 2020; Maroko et al., 2020; Wadhera et al., 2020). These studies found that variation in rates for COVID-19 deaths across the NYC boroughs was substantial. Maroko et al. (2020) concluded that zip code tabulation area (ZCTA) with low COVID-19 diagnosis rates tended to be wealthier, have higher educational attainment, higher proportions of non-Hispanic white residents, and more workers in managerial occupations. Similarly, Wadhera et al. (2020) found that the Bronx, which has the largest proportion of racial/ethnic minorities, the most persons living in poverty, and the least education level, showed higher rates of COVID-19 death than the other four boroughs.

COVID-19 is highly contagious. As social interaction is the basis of community transmission of the virus, community-level conditions that increase the chances of viral infection and proliferation could catalyze the spread of the COVID-19 (Yu et al., 2020). Congested housing, high proportion of residents in essential work, and clusters of residents with pre-existing condition are health-compromising in the era of COVID-19 pandemic. Larger household size (Maroko et al., 2020) in the neighborhood might make it difficult to follow steps to prevent contracting COVID-19, compared with less-populated neighborhoods. Furthermore, in areas where residents are more likely to work in industries like meat-packing plants, grocery stores, and factories, residents must be at the job site despite the chances of getting infected at work and bringing the virus back to the residential community (CDC, 2020). These areas would be more rapidly and severely impacted. The vulnerability of these areas may be worsened due to a higher prevalence of comorbidities or underlying conditions such as asthma, diabetes,

and other conditions (Maroko et al., 2020). These conditions for virus proliferation will be met in segregated neighborhoods afflicted with poverty, all health-compromising conditions, and discrimination. The degree of racial residential segregation in the USA remains high for minorities, especially for African Americans. This segregation puts minorities disproportionately in neighborhoods or communities with high concentrations of poverty and physical environments that place them at higher risk for a variety of diseases. This corroborates the aforementioned disparities in COVID-19. We thus speculate that communities with higher racial residential segregation are likely to have higher COVID-19 infections and deaths.

The impact of the aforementioned conditions on the spread of COVID-19 might change over time as the residents further embrace social distancing and the city started reopening in an incremental way. Since the first case of COVID-19 in NYC on February 29, 2020, the NYC has experienced multiple phases of the battle against COVID-19. The stay-at-home order took into effect on March 22, 2020, then the state officials set up a process to restart the city gradually. From Phase 1 (started on June 8, 2020) to phase 4 (started on July 20, 2020), more and more nonessential businesses were allowed to resume. At the same time, community understanding of the rationale for intervention strategies was deepening and community confidence in their ability to adopt or sustain the recommendations was rising. All these changes over time might interfere the mechanism through which neighborhood conditions, including residential segregation, impacts risks of COVID-19 and the magnitude of the impact. Therefore, this study aims to assess whether the rate of the growth of cases and deaths across the days in each ZCTA (the effect of day) would vary in magnitude as a function of the residential segregation and other socio-demographic characteristics of the ZCTA. Therefore, we hypothesize that the association between racial residential segregation and COVID-19 infections and deaths weakens over days.

Redlining and Racial Residential Segregation

Racial residential segregation in the USA was shaped by institutional racism, including unfair housing policies enforced by the federal government and supported by economic institutions (Popescu et al., 2018; Williams & Collins, 2001). Processes contributing to patterns of racial residential segregation involve multiple sectors of society (Zhou et al., 2017) and one of the most influential process that structured residential segregation is historical US governmental policies including the practice of redlining. In the 1930s, the Home Owners' Loan Corporation (HOLC) commissioned maps to guide home lending institutions. On these maps, HOLC assigned grades to residential neighborhoods

that reflected their “mortgage security” that would then be visualized on color-coded maps. Neighborhoods designated undesirable for lenders were outlined in red and received a grade of “D”, and the practice is now known as “redlining” (Bertocchi & Dimico, 2020; Krieger et al., 2020b; McClure et al., 2019). Though the grades were based on an assessment of multiple neighborhood characteristics including class and occupation of the residents and quality of buildings, a major standard of the HOLC is the residency of African Americans and immigrants. HOLC assumed that the share of foreign and black families compromised the values of homes and security of mortgages.

Similar to the other American cities, the geography of redlining in NYC had a clear racial connotation. HOLC notes for areas rated “D” in NYC stated that areas inhabited by residents of color influenced the neighborhood desirability adversely. For instance, in the case of the Bedford-Stuyvesant in Brooklyn, agents included the following statement “Colored infiltration are definitely adverse influence on neighborhood desirability although Negroes will buy properties at fair prices and usually rent rooms” (Federal Housing Administration, 1936).

These color-coded maps and their accompanying documentation, which spans over 200 cities, helped set the rules for real estate practice for decades. The maps were widely adopted by the private banking and mortgage industry (Nardone et al., 2020b), which led to the channeling of credit and investment toward white and more affluent areas (grade A or B) and away from areas with residents of color (grade C or D) (Bertocchi & Dimico, 2020; Krieger et al., 2020a, 2020b). The institutionalized segregation of capital (e.g., loans and investments) from black people shaped the socio-spatial arrangement of goods and services (e.g., jobs and schools) in the USA. The devoid of investments and loans in redlined neighborhoods had significant negative effects on neighborhood conditions, including crowded housing, poor housing quality, lower quality services from local municipalities, and lack of amenities such as recreational facilities and establishments offering healthy food choices. The impact has been devastating for generations of racial minorities who were explicitly and unjustly denied the right to live where they preferred and to school their children where the children were most likely to flourish (Rothstein, 2017). Redlining has been illegal since the enactment of the Fair Housing Act (1968) though, the Fair Housing Act did nothing to reverse or undo patterns of residential segregation that had become deeply entrenched. Thus, the impact of redlining on spatial distribution of population has been long-lasting. The redlining policy enforced by the federal government, together with discrimination from real estate agents and home sellers limit the housing options of black Americans to the least desirable residential areas (Williams & Collins,

2001). Housing in these undesirable neighborhoods tend to be undervalued. Since homeownership is the key tool for asset accumulation and major means of intergenerational wealth transfer, redlining basically blocked black families from accumulating socioeconomic resources. This impeded the upward mobility of disadvantaged black families (Faber, 2020) and reduced the chance of breaking the existing patterns of racial residential segregation. Racial residential segregation thus turned into a self-perpetuating mechanisms, maintaining the segregation over time (Faber, 2020). In summary, generations of housing discrimination in the form of redlining and other racist practices have robbed redlined communities their wealth and contributed to and perpetuated the racial residential segregation we see today.

Racial residential segregation and its perpetuating engine, redlining, is considered key in the perpetuation of racial inequality in health. Recent research suggests that redlining resulted in lasting impacts on health outcomes (Bailey et al., 2017; Beyer et al., 2016; Jacoby et al., 2017; Massey and Denton, 1993; Mendez et al., 2011, 2012, 2014; Squires, 2017; Zhou et al., 2017). Residing in previously HOLC redlined area imposed an elevated risk for multiple health outcomes: late stage at diagnosis for cervical, breast, lung, and colorectal cancer, emergency department visits due to asthma (Nardone, et al., 2020a, 2020b), preterm birth (Krieger et al., 2020; Matoba et al., 2019), and self-rated health (McClure et al., 2019). Nardone et al. (2020b) investigated the association between the historically redlined neighborhoods and 14 health outcomes in nine U.S. cities and found that residents in historically redlined areas of Atlanta, Cleveland, Miami, and the San Francisco-Oakland metropolitan areas were more likely to have poor health than in non-redlined areas. Some other health outcomes, for instance colorectal cancer survival (Zhou et al., 2017), did not show significant association with living in redlined area. These studies are limited to one or two cities. Future work is needed to test whether the aforementioned findings can be replicated in other geographical settings.

Research on place-based relationships between historic redlining and COVID-19 disparities is limited. Bertocchi and Dimico (2020) examined the weekly deaths over the period January 1, 2020 to June 16, 2020 in Chicago and found that historically lower-graded neighborhoods display a sharper increase in mortality after the outbreak of COVID-19 epidemic. This current study will build upon previous studies and assess the relationship between historic redlining and the unequal distribution of COVID-related fatalities. COVID-19 is a contagious disease with unprecedented rate of spread, community environmental conditions could accelerate or decelerate the spread of virus, highlighting the importance of probing community characteristics and thus the social process (including redlining policies) that created

the community structure. Following this line of argument, we anticipate that historically lower-graded neighborhoods is associated with higher COVID-19 infections and deaths.

The paper is organized as follows: The Data section describes the data sources, variables, and analytical strategies. The Result section presents descriptive evidence and results from regression analysis. The Conclusion and Discussion section concludes.

Data

Our data include three major components: NYC COVID-19 data, ZCTA socio-demographic characteristics, and historic HOLC grades from HOLC maps. We used the zip code to link the three data sources. We obtained COVID-19 data between April 1, 2020 and July 7, 2020 for the ZCTAs in NYC from New York City Department of Health and Mental Hygiene's Incident Command System for COVID-19 Response. The ZCTA characteristics are from the American Community Survey (ACS) 5-Year Data (2014–2018). The ACS is an ongoing survey that provides data every year, providing communities with the current information they need to plan investments and services. The ACS covers a broad range of topics about social, economic, demographic, and housing characteristics of the U.S. population.

We included maps created by HOLC from 1935 onwards in NYC. The maps are publicly available and were downloaded from the University of Richmond's Mapping Inequality Project (Nelson et al. 2020). Neighborhoods appraised by HOLC were shaded in one of four colors denoting risk, from lowest to highest: green (best), blue (still desirable), yellow (declining), red (hazardous). We overlapped the HOLC maps with NYC map using ArcGIS. The overlapped map shows that ZCTAs do not have 100% of their land area contained entirely within one larger HOLC area, but span across multiple HOLC areas and not HOLC-coded areas (these neighborhoods were likely undeveloped when the maps were originally created). We thus calculated the HOLC graded areas in each ZCTA and computed its percentage (HOLC graded areas divided by total areas in the ACTA) using python library GeoPandas.

Variables

The dependent variables contain the cumulative percentage of people who tested positive (positive residents/tested residents) from April 1, 2020 to July 8, 2020 and cumulative death rate from June 8, 2020 to July 8, 2020, by ZCTA of residence. ZCTA combines census blocks with smaller populations to allow more stable estimates of population size for rate calculation. The cumulative counts are as of the date of extraction from the NYC Health Department's

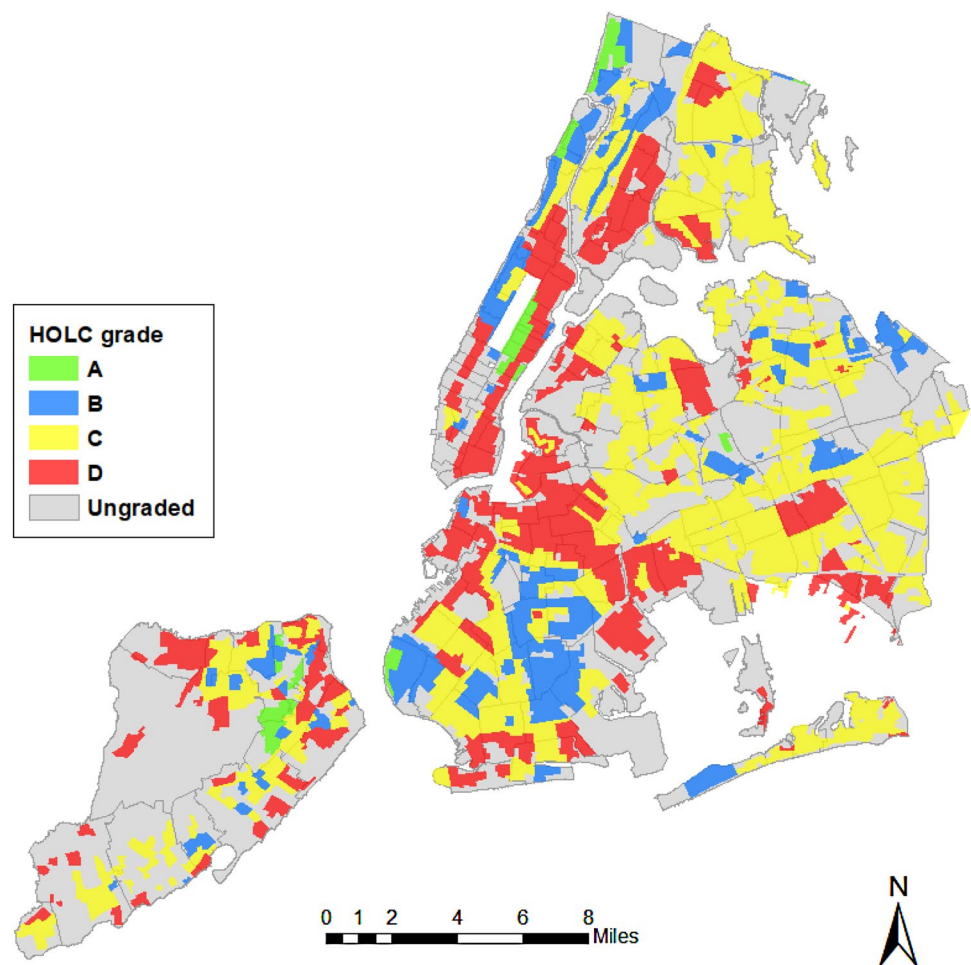
disease surveillance database. The Health Department classifies the start of the outbreak in NYC as the date of the first laboratory-confirmed case, February 29, 2020. However, data on percentage of positive cases or death rate by ZCTA from March 1, 2020 to March 31, 2020 are not available at NYC Coronavirus (COVID-19) data repository. Due to data limitation, our study was not able to analyze COVID-19 from the date when the first case of COVID-19 in NYC was identified. We analyzed cumulative death rate a month from the start of the phase 1 (June 8, 2020 to July 8, 2020); June 8, 2020 is the start of the phase 1 of reopening. For the cumulative percentage of people who tested positive (positive residents/tested residents), we included data both before and after the phase 1 reopening (April 1, 2020 to July 8, 2020).

The independent variables include the racial/ethnic composition of each ZCTA, as indicators for the racial residential segregation in the ZCTA. Studies on racial residential segregation at zip code level have been adopting racial/ethnic composition as a proxy for segregation (Kershaw et al., 2015; White & Borrell, 2011). We calculated the proportion of Hispanic and black by dividing the size of each

racial group with the total population. Although literature on racial disparities of COVID-19 have been mostly focused on the black and Hispanic, we also included the proportion of Asian groups as a control variable. Asian Americans have been reported dying from COVID-19 at alarming rates, while facing with Anti-Asian Racism fueled by COVID-19 (Le et al., 2020). The proportion of Natives in NYC is extremely small, and thus is not included in the study. The data were obtained from 2018 American Community Survey 5-year estimates.

Another major variable of interest is HOLC assigned grade in ZCTAs. In Fig. 1, four HOLC grades, including best (grade A), still desirable (grade B), declining (grade C), and hazardous (grade D), are denoted in green, blue, yellow, and red, respectively. As aforementioned, ZCTAs don't have 100% of their land area contained entirely within one larger HOLC area, but span across multiple HOLC areas and not HOLC-coded areas. For ZCTAs overlapping multiple HOLC areas, the higher HOLC grade within a ZCTA, whether grade A or grade B, are expected to gain access to more and better-quality community services and amenities including health-relevant resources like public green space

Fig. 1 The HOLC map for the New York City



or hospitals. These resources surrounding the better-off communities have a chance of ‘spilling over’ to benefit worse off communities geographically adjacent to the better-off communities (Levy et al., 2010); thus influence health and diagnose and treatment of disease in the ZCTA. We thus extracted the highest HOCL grade in the ZCTAs and examined its association with COVID-19 fatalities. The proportion of HOLC areas in the ZCTA varies from 0.002 to 1. We used 0.1 as the cutoff to define the ungraded ZCTAs and identified 8 ungraded ZCTAs. After excluding these ungraded ZCTAs from our study, there are 21 (12.72%) ZCTAs with a highest HOLC grade of A for, 76 (46.06%) ZCTAs with a grade of B, 52 (31.52%) ZCTAs with a grade of C, and 16 (9.70%) ZCTAs grade of D.

We included the following socio-demographic characteristics in the ZCTAs as control variables: proportion of old population (65 years and over), proportion of population with lower than high school degree, household median income, and household size. The risk for severe illness from COVID-19 has been found to be higher for older adults; thus, higher percentage of population 65 years and over might be associated with higher COVID-19 infection and death. Denser household face more difficulties practicing social distancing; therefore, would likely to be more rapidly and severely impacted. We also included percentage of population tested in the ZCTA.

Descriptions of cumulative percentage of people who tested positive (April 1, 2020–July 8, 2020), cumulative death rate (June 8, 2020–July 8, 2020), and percentage of population tested by ZCTA of residence are provided in Table 1. We calculated average percentage of people who tested positive, average cumulative death rate, and average percentage of population tested based on the highest HOLC assigned grade in ZCTAs. We used ANOVA tests to test the differences among ZCTAs with different HOLC assigned grade. Similarly, we presented racial compositions and other ZCTA-level factors based on the highest HOLC assigned grade in ZCTAs in Table 2. ANOVA tests was used to determine whether there are any statistically

significant differences between the means of groups with different HOLC assigned grade.

Methods

We started our analysis by calculating the correlations of all dependent variables and the covariates (except HOLC assigned grade in ZCTAs). We then adopted a two-level mixed effect linear regression models to fit the relationship between independent variables and cumulative daily cases/deaths of COVID-19 (level-1) in the ZCTAs (level-2). These models assessed whether the change of positive cases and deaths across the days in each ZCTA would vary as a function of ZCTA socio-demographic characteristics including proportion of each racial group and the redlining of the ZCTA. Covariates, all assessed at the ZCTA level, including proportion of population 65 years and over, proportion of population with lower than high school degree, household median income, and household size were introduced into the model sequentially.

This study used two-level linear regression models to investigate the variation of COVID-19 cumulative daily positive cases and deaths over time and over spaces. The data used in the current study are structured hierarchically: The 15,252 daily observations were nested within 163 ZCTAs. It may be unrealistic to assume that the cases/deaths over time in the same ZCTA are uncorrelated, given that the cases/deaths could be determined by unobserved characteristics shared within the ZCTA. We thus used multilevel models to account for the clustering of daily observation within the ZCTA. Each model estimated a random intercept, to allow for heterogeneity across ZCTA. The likelihood ratio test was used to compare multilevel models and single-level models, and the results indicated that multilevel model was superior. The estimation equation can be presented as:

$$y_{ij} = (\beta_1 + \zeta_j) + \beta_2 day_{ij} + \beta_3 day_{ij}^2 + \beta_4 x_{1ij} \dots + \beta_p x_{pij} + \epsilon_{ij} \tag{1}$$

Table 1 Summary statistic of COVID-19 cases and deaths by the highest HOLC grade

	A (N= 1973)	B (N= 7237)	C (N= 4888)	D (N= 1504)	Total (N= 15,602)	p value
The cumulative percentage of people who tested positive (April 1st–July 8th)						
Mean (SD)	29.896 (13.234)	35.615 (15.335)	38.100 (15.371)	32.439 (14.853)	35.364 (15.279)	<0.001
Cumulative COVID death rate (June 8th–July 8th)						
Mean (SD)	185.232 (93.953)	201.786 (99.480)	203.591 (90.770)	180.586 (94.320)	198.271 (95.939)	<0.001
Percentage of COVID-tested population						
Mean (SD)	0.076 (0.046)	0.069 (0.042)	0.070 (0.041)	0.069 (0.046)	0.070 (0.043)	<0.001

Table 2 Summary statistic of ZCTAs characteristics by the highest HOLC Grade

	A (N=21)	B (N=76)	C (N=52)	D (N=16)	Total (N=165)	p value
Median household income						
Mean (SD)	86,485.524 (32,478.724)	67,807.118 (28,187.214)	65,684.558 (17,752.597)	60,340.562 (31,651.169)	68,791.412 (27,058.998)	0.009
Proportion of old population						
Mean (SD)	0.189 (0.045)	0.147 (0.042)	0.134 (0.039)	0.124 (0.037)	0.146 (0.045)	<0.001
Proportion of Hispanic population						
Mean (SD)	0.266 (0.217)	0.250 (0.198)	0.285 (0.174)	0.323 (0.208)	0.270 (0.194)	0.507
Proportion of white population						
Mean (SD)	0.657 (0.185)	0.456 (0.255)	0.377 (0.254)	0.393 (0.219)	0.451 (0.257)	<0.001
Proportion of black population						
Mean (SD)	0.092 (0.094)	0.218 (0.247)	0.282 (0.294)	0.249 (0.209)	0.225 (0.251)	0.032
Proportion of Asian population						
Mean (SD)	0.093 (0.063)	0.162 (0.159)	0.149 (0.138)	0.141 (0.139)	0.147 (0.142)	0.281
Proportion of population with lower than high school degree						
Mean (SD)	0.082 (0.065)	0.119 (0.062)	0.125 (0.047)	0.150 (0.068)	0.119 (0.060)	0.005
House hold size						
Mean (SD)	2.355 (0.430)	2.705 (0.507)	2.831 (0.461)	2.369 (0.466)	2.670 (0.506)	<0.001

In the equation, y_{ij} represents the cumulative percentage of positive cases (death rate) of ZCTA j at day i ; x_{ij} through x_{pij} are ZCTA-level variables; ε_{ij} is the random error; and level-2 residual ζ_j is a ZCTA-specific error component, which remains constant across days. All predictors in the model (except for day and HOLC assigned grade in ZCTAs) were z-scored. It is worthwhile to point out that we also estimated growth curve models with random slope across days for ZCTA; however, the model did not converge well. We thus did not include growth curve models in the results. All analyses were performed in R, version 4.0.2.

Results

Both the percentage of people who tested positive and the death rate are mapped according to each ZCTA in Fig. 2. Clusters of high percentage of people who tested positive were present in areas of south Bronx, north and east Queens, north Brooklyn, and north Staten Island, and clusters of high COVID-19 death rate were identified throughout south Bronx and areas in east and north Queens. These hot spots are areas with higher proportion of black and Hispanic population.

The patterns reflected in Fig. 2 are consistent with the result of correlation analysis. The correlation between the percentage of people who tested positive and the proportion of the Hispanic population is positive, indicating that as the percentage of people tested positive increases in the ZCTA, we expect that the proportion of Hispanic in the ZCTA is higher; so is the correlation between percentage of people who tested positive and proportion of black population. As for death rate, its correlation with the proportion of Hispanic population and proportion of black population is positive, respectively. It indicates that in ZCTAs with a higher proportion of Hispanic population and black population, there is a higher COVID-19 death rate. Other variables, including the proportion of white population and median household income are negatively correlated to both percentage of people tested positive and death rate (Fig. 3).

COVID-19 positive cases and deaths also differ for ZCTAs with different HOLC grade. The distribution of percentage of people who tested positive and death rate is shown separately for each HOLC grade in Table 1 and ZCTAs characteristics are presented in Table 2. Compared with lower-graded ZCTAs, grade A ZCTAs have lower percentage of people who tested positive, higher percentage of COVID-tested population, higher median household income,

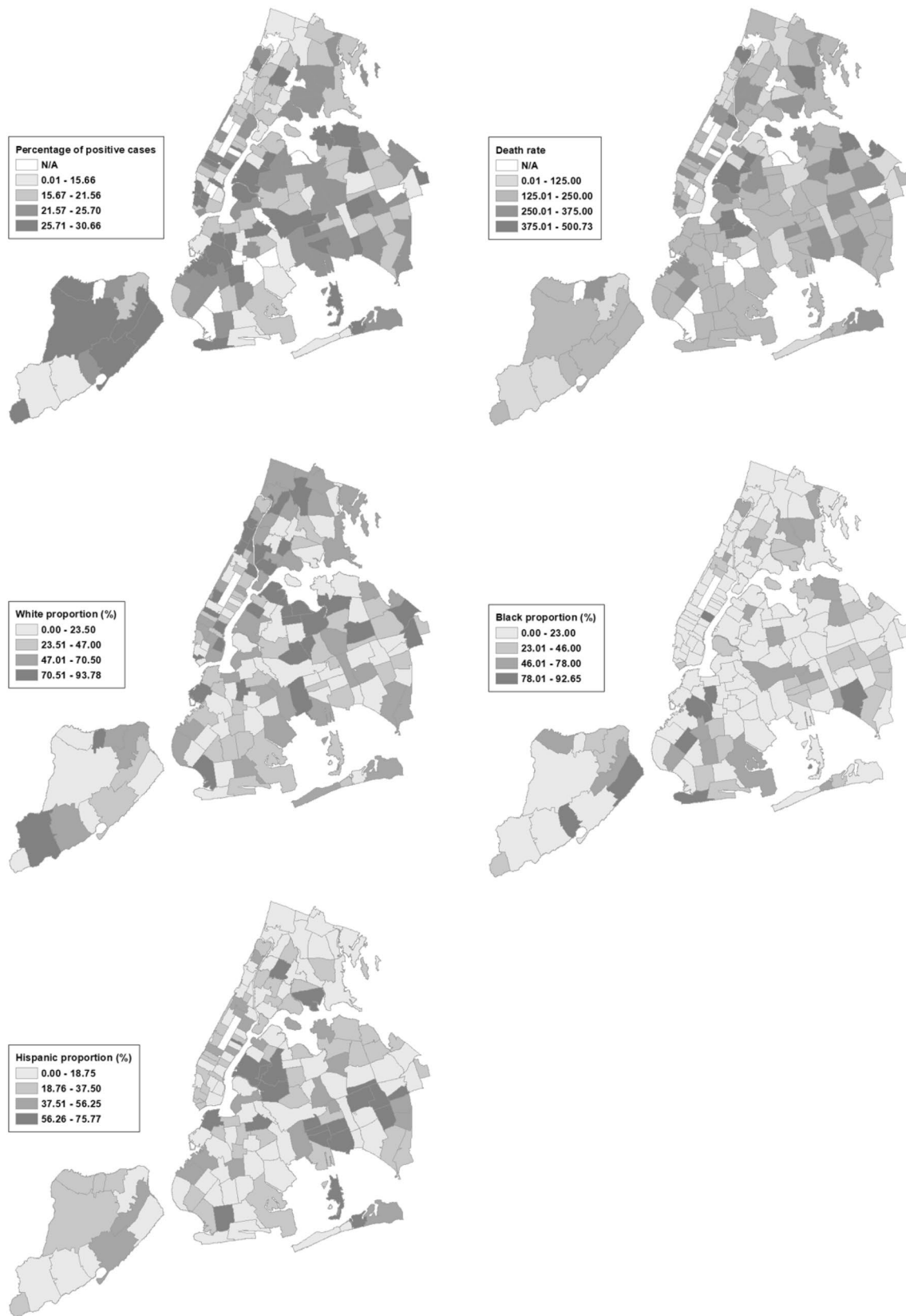


Fig. 2 Spatial distribution of the percentage of people who tested positive (top-left), death rate (top-right), Proportion of white population (middle-left), Proportion of black population (middle-right), and Proportion of Hispanic population (bottom-left) across NYC

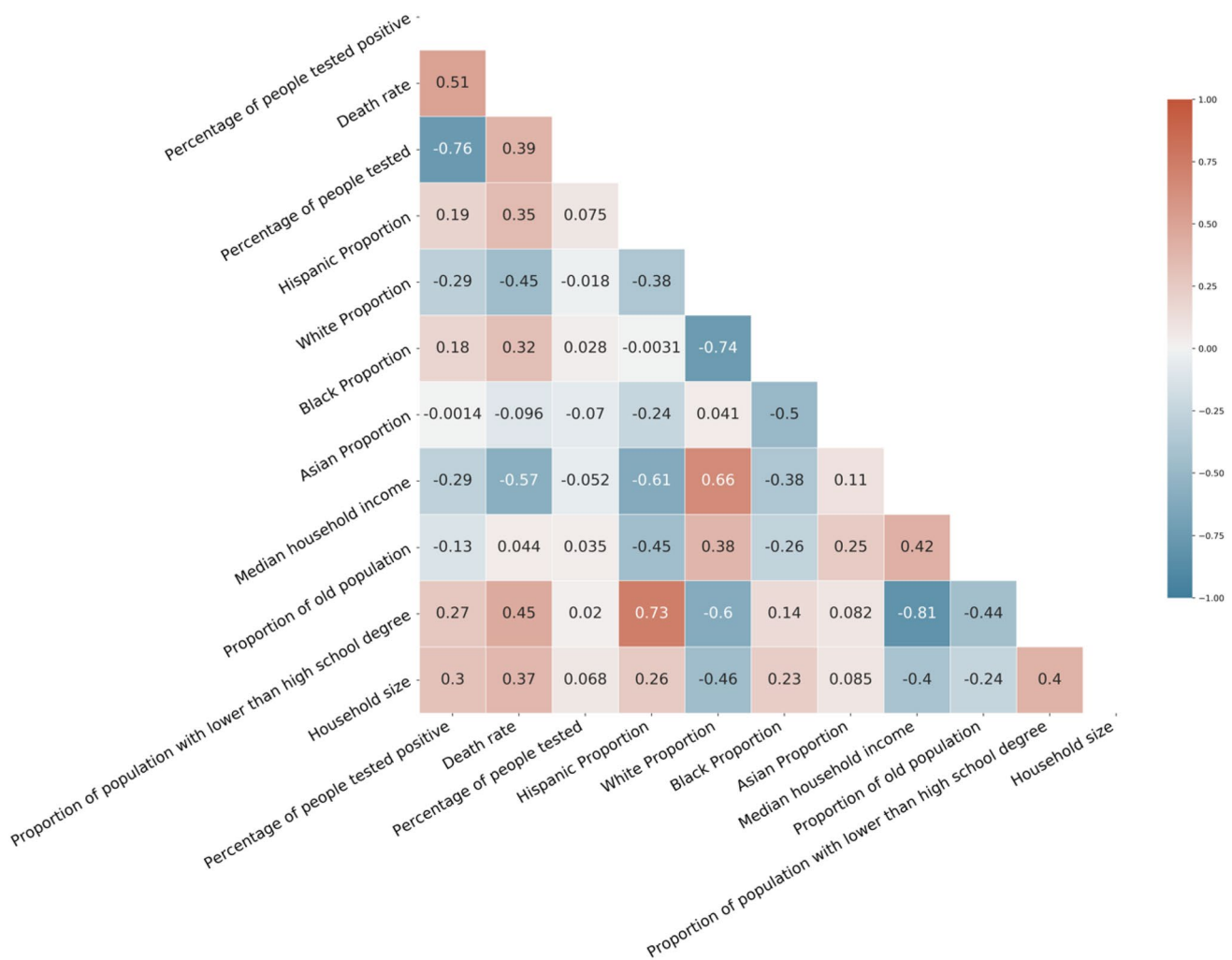


Fig. 3 Correlation matrix of the dependent and independent variables. Note: All the correlations are significant at 0.001 level except for the following: percentage of population tested is not significantly correlated with proportion of white population, proportion of black

population, and proportion of population with lower than high school degree; correlation between proportion of black population and proportion of Hispanic population is not significant either

higher proportion of old population, lower proportion of black population and Hispanic population, smaller household size and lower percentage of population with lower than high school degree. The COVID-19 death rate in grade A ZCTAs is lower than ZCTAs where highest HOLC grade is B and C, but not lower than ZCTAs where highest HOLC grade is D.

We further tested the association between the percentage of people tested positive, racial composition, and HOLC grade in the ZCTA using multilevel regression analysis, as presented in Table 3. Model 1 shows a higher proportion of Hispanic population and a higher proportion of black population is significantly related to a higher percentage of people who tested positive, when day, square of day, the proportion of Asian population, and the percentage of population tested in the ZCTA are held constant. In model 2, the

positive association between the proportion of Hispanic and black population and the percentage of people who tested positive remains significant, when more factors regarding ZCTA characteristics including the proportion of old population, median household income, and household size are included in the model. In model 3, highest HOLC assigned grade in the ZCTA is introduced into the model. ZCTAs where highest HOLC grade is C shows significant higher percentage of people who tested positive, compared with ZCTAs where highest HOLC grade is A. In model 4, the interaction term between day and major ZCTA characteristics are further included into the model. The interaction term between proportion of black population and day is significantly negatively related to percentage of people who tested positive, indicating as tracking day increases, the association between the proportion of black population and the

Table 3 Regression analysis for percentage of population who tested positive (April 1st, 2020–July 8th, 2020)

	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	58.76*** (0.41)	58.82*** (0.33)	57.26*** (0.86)	56.83*** (0.88)	53.51*** (0.90)
Percentage of Hispanic population	4.02*** (0.90)	2.80*** (0.74)	2.76*** (0.72)	3.96*** (0.74)	3.99*** (0.75)
Proportion of black population	4.77** (1.67)	4.45*** (1.28)	4.25*** (1.23)	5.92*** (1.27)	5.67*** (1.29)
Proportion of white population	0.51 (1.55)	2.17 (1.19)	2.12 (1.14)	2.18 (1.18)	2.31 (1.20)
Proportion of Asian population	3.16** (1.03)	2.22** (0.77)	1.98** (0.75)	3.65*** (0.77)	3.35*** (0.78)
Day	−0.60*** (0.00)	−0.60*** (0.00)	−0.60*** (0.00)	−0.60*** (0.00)	−0.53*** (0.01)
Square of the day	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)
Percentage of people get tested	−2.04*** (0.13)	−2.02*** (0.13)	−2.01*** (0.13)	−2.32*** (0.12)	−2.67*** (0.12)
Proportion of old population		0.76* (0.32)	0.96** (0.33)	0.99** (0.34)	1.02** (0.35)
Median household income		−1.31* (0.52)	−1.24* (0.51)	−1.27* (0.51)	−1.29* (0.52)
Household size		3.19*** (0.31)	2.82*** (0.31)	2.85*** (0.32)	2.88*** (0.32)
Proportion of population with lower than high school degree		0.52 (0.63)	0.82 (0.62)	0.79 (0.63)	0.75 (0.64)
Highest HOLC assigned grade in the zip code is B			1.71 (0.94)	1.68 (0.95)	4.90*** (0.98)
highest HOLC assigned grade in the zip code is C			2.74** (1.01)	2.71** (1.03)	6.24*** (1.06)
Highest HOLC assigned grade in the zip code is D			−0.79 (1.25)	−0.80 (1.27)	1.53 (1.31)
Proportion of Hispanic population*Day				−0.02*** (0.00)	−0.02*** (0.00)
Proportion of black population*Day				−0.03*** (0.00)	−0.03*** (0.00)
Proportion of white population*Day				−0.00 (0.00)	−0.00 (0.00)
Proportion of Asian population*Day				−0.03*** (0.00)	−0.03*** (0.00)
Highest HOLC assigned grade is B*Day					−0.07*** (0.00)
highest HOLC assigned grade is C*Day					−0.07*** (0.00)
Highest HOLC assigned grade is D*Day					−0.05*** (0.00)
N	15,438	15,345	15,345	15,345	15,345
N (zipcode)	165	164	164	164	164
AIC	81,023.98	80,448.03	80,434.00	78,963.70	78,414.09
BIC	81,100.42	80,554.97	80,563.85	79,124.11	78,597.42
R ² (fixed)	0.87	0.91	0.91	0.91	0.91

Table 3 (continued)

	Model 1	Model 2	Model 3	Model 4	Model 5
R^2 (total)	0.96	0.96	0.96	0.96	0.96

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$

percentage of people who tested positive becomes weaker. Interaction between the proportion of Hispanic population and day is also statistically significant. Model 5 includes the interaction between highest HOLC grade and the day. The interaction term is significant. It suggests that as the days increase, the difference in percentage of population tested positive between ZCTA with lower HOLC grade and where highest HOLC is A becomes smaller.

We performed a similar two-level linear regression on the COVID-19 death rate, as shown in Table 4. Model 6 shows that when day, square of the day, and the proportion of population tested are controlled, the proportion of Hispanic population has a significant and positive association with the death rate. However, there is not significant association between the proportion of black population and death rate. When we additionally controlled for a few more variables on ZCTA characteristics in model 7, the association between the proportion of Hispanic population and death rate is not significant anymore. Unlike in the analysis of confirmed positive cases, the death rate of ZCTA where highest HOLC grade is B, C, and D did not show significant difference from ZCTA where highest HOLC is A. In model 9, the two-way interaction term with day is introduced into the model. The interaction term between the proportion of black population and day shows significant positive association with death rate, indicating as tracking day increases, the association between the proportion of black population and death rate becomes stronger. So does the interaction between the proportion of Hispanic population and day. Model 10 included the interaction between highest HOLC grade and the day. The interaction terms are significantly positive. It suggests that as the days increase, the difference in death rate between ZCTA with C grade and ZCTA with A grade becomes greater.

Across all the models, there are some notable associations between covariates and the outcomes. These associations are largely consistent across both outcomes. These statistics reported here are based on models when the outcome is the percentage of population tested positive. Day is negatively related to the outcome, suggesting as the day increases the percentage of population tested positive decreases. Proportion of old population and household size is significantly positively related to percentage of people tested positive, while proportion of people tested and median household income is significantly negatively related to percentage of people tested positive. Proportion of population with lower

than high school degree and proportion of white population in the ZCTA do not show significant relationship with percentage of people tested positive. Interaction between day and other ZCTA characteristics including percentage of old population and household size are significantly positive. The proportion of Asian population showed different association with the two outcomes. Higher proportion of Asian population in the ZCTA is significantly associated with higher percentage of people tested positive, while not significant related to death rate.

Robustness Checks

To check the robustness of the findings above, we carried out three variations of the main analysis. In the first variation, we analyzed only the time period before the first phase open (from April 1, 2020 to June 8, 2020). Focusing on a shorter period might help minimize bias from certain confounding conditions. For instance, reporting biases and test capacity are less likely to vary systematically within a shorter time period (Yu et al., 2020). The results are largely consistent with results from extended observation periods (April 1, 2020 to July 8, 2020). ZCTAs where highest HOLC grade is C shows a significantly higher percentage of people who tested positive, compared with ZCTA where highest HOLC grade is A. The HOLC grade and day interaction remains significant. In the second variation, instead of 0.1, 0.2 and 0.3 are used as the cutoff to define the ungraded ZCTAs, respectively. The effect of HOLC grade does not change sensibly whichever cutoff value we use. With the 0.2 cutoff, 16 ZCTAs are identified as ungraded. We conduct regression analysis after excluding these ungraded ZCTAs and the results shows that the 2-way interactions remain significant. Lastly, our data, as aforementioned, are aggregated at ZCTA level; a ZCTA could overlap multiple HOLC areas. To explore problems that may be raising due to aggregation, we isolated ZCTAs including only one HOLC grade and compared results from this subsample with the full samples. Reassuringly, the results from 34 ZCTAs (20%) with single HOLC grade are consistent with results from full samples. Regression results indicated ZCTAs with only D-graded areas showed lower percentage of people tested positive, compared with ZCTAs with only C-graded areas. We were not able to compare ZCTAs with only A-graded or B-graded areas, as ZCTAs with single HOLC grade have a grade of

Table 4 Regression analysis for death rate (June 8th, 2020–July 8th, 2020)

	Model 6	Model 7	Model 8	Model 9	Model 10
Intercept	248.14*** (9.97)	249.08*** (9.30)	247.26*** (20.35)	254.92*** (19.98)	260.47*** (19.88)
Proportion of Hispanic population	45.86** (16.51)	27.52 (15.40)	27.84 (15.67)	19.53 (15.56)	19.38 (15.38)
Proportion of white population	14.82 (28.64)	17.47 (24.76)	17.52 (24.98)	3.36 (24.84)	4.71 (24.55)
Proportion of black population	56.13 (30.82)	36.72 (26.55)	37.15 (26.85)	2.95 (26.70)	4.47 (26.39)
Proportion of Asian population	28.38 (18.95)	6.50 (16.05)	6.53 (16.33)	− 16.77 (16.24)	− 15.50 (16.05)
Day	− 2.04*** (0.18)	− 2.05*** (0.19)	− 2.05*** (0.19)	− 2.19*** (0.18)	− 2.30*** (0.18)
Square of the day	0.02*** (0.00)	0.02*** (0.00)	0.02*** (0.00)	0.02*** (0.00)	0.02*** (0.00)
Percentage of people get tested	− 6.96*** (0.99)	− 6.73*** (0.99)	− 6.74*** (0.99)	− 2.45* (1.01)	0.76 (1.03)
Proportion of old population		43.36*** (6.62)	43.12*** (7.29)	42.66*** (7.18)	42.32*** (7.10)
Median household income		− 45.04*** (10.93)	− 44.40*** (11.09)	− 44.11*** (10.91)	− 43.90*** (10.79)
Household size		19.79** (6.56)	18.91** (7.00)	18.62** (6.89)	18.41** (6.81)
Proportion of population with lower than high school degree		1.58 (13.15)	2.43 (13.47)	3.07 (13.26)	3.54 (13.11)
Highest HOLC assigned grade in the zip code is B			5.00 (20.94)	5.56 (20.62)	9.49 (20.56)
highest HOLC assigned grade in the zip code is C			0.37 (22.54)	0.89 (22.19)	− 11.64 (22.12)
Highest HOLC assigned grade in the zip code is D			− 6.49 (27.56)	− 6.72 (27.13)	19.18 (27.06)
Proportion of Hispanic population*Day				0.09*** (0.03)	0.08** (0.02)
Proportion of black population*Day				0.42*** (0.05)	0.39*** (0.05)
Proportion of white population*Day				0.17*** (0.04)	0.15*** (0.04)
Proportion of Asian population*Day				0.29*** (0.03)	0.27*** (0.03)
Highest HOLC assigned grade is B*Day					− 0.04 (0.03)
highest HOLC assigned grade is C*Day					0.16*** (0.04)
Highest HOLC assigned grade is D*Day					− 0.33*** (0.05)
N	5576	5542	5542	5542	5542
N (zipcode)	163	162	162	162	162
AIC	40,389.11	40,092.15	40,075.07	39,653.83	39,492.73
BIC	40,455.37	40,184.83	40,187.61	39,792.85	39,651.61
R ² (fixed)	0.25	0.48	0.48	0.48	0.49

Table 4 (continued)

	Model 6	Model 7	Model 8	Model 9	Model 10
R^2 (total)	0.99	0.99	0.99	0.99	0.99

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$

either C or D. Robustness analyses results are not presented but are available upon request.

Discussion and Conclusion

The disproportionate number of fatalities among racial minority groups in the current COVID-19 pandemic has brought to the foreground the deep health divides within American society. This study set out to test the influence of a range of community-level factors on fatalities of COVID-19. Most important among these is racial residential segregation. Our findings illustrate that the higher proportion of black and Hispanic populations in the ZCTAs are significantly related to the higher percentage of people who tested positive. Besides current-day residential segregation, historic housing policies were also found to have an impact on COVID-19 infection rates among minority groups. Compared with HOLC-defined desirable areas, historically lower-graded neighborhoods are at a higher risk for COVID-19 infection in ZCTAs with present-day economic and racial privilege. The residents in disadvantaged areas and neighborhoods are often blamed for the resulting problems, though the institutional racism in the form of residential housing segregation is arguably the cause that channeled them into the disadvantaged neighborhoods. The influence of historical redlining not only suggests the need for public health outreach to vulnerable populations, but also helps inform debates over policy and resource allocation to promote fair housing.

The data confirm that segregated neighborhoods that have a higher percentage of Hispanic and black populations have more cases of COVID-19. This result is consistent with previous studies at state and county levels. States with a higher proportion of people who reported African American race or other races were found to have higher death rates, despite accounting for state level differences (Sehra et al., 2020). At the county level, the growth rate for COVID-19 confirmed cases was higher for the areas with higher proportion of non-whites (Millett et al., 2020; Yu et al., 2020). Hispanic and black populations might have been disproportionately exposed to physical environments that place them at higher risk for COVID-19. Ethnic/racial minorities are likely to hold essential jobs in food and agriculture, industrial, commercial and residential facilities and services, and other sectors, putting them on the front line and at risk of exposure to COVID-19 (Bhala et al., 2020). The

association between these aforementioned factors weaken as the pandemic unfolds. This might be explained by intensifying governmental intervention that is directing resources to disadvantaged areas.

Furthermore, by combining the spatial distribution of infection and death with the redlining maps of NYC, we were able to examine the impacts of pandemic on the historically low-graded neighborhoods. The results indicate that historical redlining contributes to COVID-19 inequalities, above and beyond current neighborhood conditions. Historically low-graded neighborhoods display a higher COVID-19 infection. We did not find a significant relationship between redlining and COVID-19 mortality. This does not necessarily deny the possible impact of redlining, given our study was limited to mortality in June 8, 2020 to July 8, 2020. Despite the high number of COVID-19 deaths in March and April 2020, by June, NYC had reduced the rate of increase of death to a very low level. The city reported only 33 confirmed COVID-19 deaths on June 8 and the 7-day average of confirmed COVID-19 deaths in June and early July was consistently under 40. This might be partially because that individual's and community's respect and ability to adopt the social distancing and hygiene practices was rising as the pandemic unfolds. Hospitals were also better equipped to treat COVID-19 and its complications. This might imply that persistent government interventions at NYC were effective at reducing the inequalities in COVID-19 fatalities. A study based on COVID-19 mortality from January 1, 2020 to June 16, 2020 in Chicago found that historically lower-graded neighborhoods display a sharper increase in mortality (Bertocchi & Dimico, 2020). The discrepancy in the conclusions might be explained by differing study period and dissimilar intensity of government interventions in NYC and Chicago.

The attested association of historic redlining and COVID-19 disparities illustrate that structural racial inequalities transform into health inequalities and reify health disparities. Racial residential segregation and resulting disparities in access to housing, wealth, and health resources did not emerge naturally, but were socially produced and imposed upon the marginalized largely through discriminatory and inequitable government policies and actions like redlining. Segregation's effects on physical infrastructure, local investment patterns, and wealth accumulation work in tandem to increase the likelihood that minority neighborhoods bear a disproportionate burden of a pandemic. Housing, the basic of one's living environment, is key to COVID-19 because

our current best defense against the virus is social distancing. However, housing is not equally accessible to all, instead housing insecurity is rife in the USA during the COVID-19 pandemic. Disadvantaged populations, especially communities of color, are facing housing issues varying from poor conditions, instability, and even eviction/loss. Those precariously housed have difficulty practicing physical distancing and self-isolation difficult, which therefore exposes them to the risks of infections.

Since long before the COVID-19 pandemic, racial residential segregation and the resultant housing inequality have been entrenched in American Society. Households in historically low-graded neighborhood have been experiencing great levels of hardship, ranging from plunging property values to insufficient infrastructure support of basic needs like healthy food options and health care services. The COVID-19 pandemic not only brought to light this existing crisis but exacerbated the housing and housing-related disparities as well. The COVID-19 pandemic has led to a historically high rate of unemployment, which in turn has worsened the existing housing instability among lower-income families. The soaring eviction rate is expected as a consequence of the COVID-19 pandemic (Sehra et al., 2020). Especially, housing hardships tend to limit minority groups to ghettos or homelessness. This could reinforce the existing racial residential segregation. Eviction and housing displacement pose a particular health risk during the pandemic, as once-tenants double up with friends or relatives or resort to homelessness. These conditions reduce social distancing and sanitation, especially in the case of homelessness.

Now that the coronavirus pandemic has brought the stark inequalities to the foreground, it is imperative that public practitioners act on housing as a tool to ameliorate housing-related disparities, especially housing-related health disparities in terms of ability to social distance and access to health care. Given that it is the deep historical roots and the continuing practices in law and social custom that intentionally promoted and enforced a profoundly residential segregation, effectively targeted solutions to prevent and alleviate housing disparities must occur at the policy level fully and immediately. Effort to formulate an effective recovery-from-pandemic plan without awareness of how housing is inextricably related to COVID-19 fatalities will not likely come to great fruition. Besides the impact of housing on health during the pandemic, housing is undoubtedly a necessity that individuals deserve equal access to. The Coronavirus Aid, Relief, and Economic Security Act (the CARES Act) has been playing a positive role in relieving individual housing burden during the pandemic by offering rental assistance. However, the CARES Act serves more like a temporary response to the housing problem that spans larger than the COVID-19 pandemic. We must move from a band-aid solution to a long-term solution. Given that the origins of

housing disparities are rooted in fundamentally unjust and explicit government policies at all levels, to alleviate housing disparities, past injustices must be corrected at the policy level. Using inverted versions of HOLC maps to guide contemporary investment could be a step toward housing fairness and racial equality (Faber, 2020).

Some limitations of the current work must be noted. First, our study is limited by the fact that it represents an ecological analysis and does not use individual-level data. Individual-level factors that may impact COVID-19 spread and test were not able to be examined here. The results do not necessarily apply to the individuals living in the neighborhoods. Second, due to data limitation, our study did not analyze COVID-19 from the date when the first case of COVID-19 in NYC was identified, which was February 29, 2020. In this study, we analyzed cumulative death rate a month from the start of the phase 1 (June 8, 2020 to July 8, 2020); June 8, 2020 is the start of the phase 1 of reopening. For the cumulative percentage of people who tested positive (positive residents/tested residents), we included data both before and after the phase 1 reopening (April 1, 2020 to July 8, 2020). Lieberman-Cribbin et al. (2020) examined disparities in COVID-19 testing and positivity in NYC using data from March 2, 2020 to April 6, 2020. They found that the ratio of positive tests significantly decreased with the increasing proportion of white residents in the ZCTA (Lieberman-Cribbin et al., 2020), while we did not see this association in our analysis. This discrepancy might suggest the changing influence of proportion of white residents as the pandemic unfolds, necessitating efforts to examine different phases of the coronavirus pandemic. Thirdly, residential segregation is multi-dimensional, and the measure of residential segregation here, racial composition, might not entirely capture this construct. For measures of residential segregation at county or city level, studies have been using the index of dissimilarity and the index of isolation (Logan, T., & Parman, J., 2015). The National Rise in Residential Segregation (Working Paper No. 20934; Working Paper Series). National Bureau of Economic Research. <https://doi.org/10.3386/w20934>). We were not able to estimate either index for each ZCTA because we do not have data on variation in the racial composition among geographical subunits making up ZCTAs, which is required to calculate both indexes (Logan, T., & Parman, J., 2015). The National Rise in Residential Segregation (Working Paper No. 20934; Working Paper Series). National Bureau of Economic Research. <https://doi.org/10.3386/w20934>). Future studies may use alternate measure of residential segregation.

Despite these limitations, our findings point to the complexities of understanding current-day community environments including residential segregation, historical housing policies, and health inequalities. The COVID-19 pandemic has amplified structural racial inequalities in health and in

other domains. Our work provides the evidence that disparity and segregation resulting from historical redlining policies impose the minorities disproportionately to higher toll of COVID-19. Besides the current studies, researchers have found that residential segregation impacts health across a variety of measures and contexts. Our findings, together with aforementioned studies, suggest that more effort is needed to build less segregated living environments in the backdrop of the return of infectious disease. Restorative intervention at the policy level should be designed and implemented to correct past injustices and to undo the harm of unfair federal housing policies. We believe that future research on health inequalities can further investigate how historical policies can have long-standing spatial and social impacts on health.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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