Environment International 152 (2021) 106465

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Green spaces mitigate racial disparity of health: A higher ratio of green spaces indicates a lower racial disparity in SARS-CoV-2 infection rates in the USA

Yi Lu [a], Long Chen [a], Xueming Liu [b], Yuwen Yang [b,c], William C. Sullivan [d], Wenyan Xu [b,c], Chris Webster [e], Bin Jiang [b,c,*]

[a] *Department of Architecture and Civil Engineering, College of Engineering, City University of Hong Kong, Hong Kong Special Administrative Region*
[b] *Virtual Reality Lab of Urban Environments and Human Health, HKUrbanLabs, The University of Hong Kong, Hong Kong Special Administrative Region*
[c] *Division of Landscape Architecture, Department of Architecture, The University of Hong Kong, Hong Kong Special Administrative Region*
[d] *Smart, Healthy Communities Initiative, University of Illinois at Urbana-Champaign, USA*
[e] *HKUrbanLabs, Faculty of Architecture, The University of Hong Kong, Hong Kong Special Administrative Region*

ARTICLE INFO

Handling Editor: Thanh Nguyen

Keywords:
Racial disparity
Health disparity
SARS-CoV-2
COVID-19
Green space
Mechanism

ABSTRACT

There is striking racial disparity in the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infection rates in the United States. We hypothesize that the disparity is significantly smaller in areas with a higher ratio of green spaces. County level data on the SARS-CoV-2 infection rates of black and white individuals in 135 of the most urbanized counties across the United States were collected. The total population in these counties is 132,350,027, comprising 40.3% of the U.S. population. The ratio of green spaces by land-cover type in each county was extracted from satellite imagery. A hierarchical regression analysis measured cross-sectional associations between racial disparity in infection rates and green spaces, after controlling for socioeconomic, demographic, pre-existing chronic disease, and built-up area factors. We found a higher ratio of green spaces at the county level is significantly associated with a lower racial disparity in infection rates. Four types of green space have significant negative associations with the racial disparity in SARS-CoV-2 infection rates. A theoretical model with five core mechanisms and one circumstantial mechanism is presented to interpret the findings.

1. Introduction

Racial disparity in health is a significant problem in many countries and can lead to social conflicts, economic crises, and loss of life (Blendon et al., 1995; Kawachi et al., 2005). The black-white health disparity in the United States is representative of many developed economies and is unsurprisingly manifest in the ongoing coronavirus disease 2019 (COVID-19) pandemic (Figueroa et al., 2020; Webb Hooper et al., 2020; Wrigley-Field, 2020; Yancy, 2020). COVID-19 results from infection with severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), and the SARS-CoV-2 infection rate in black individuals is significantly higher than that in white individuals (Figueroa et al., 2020; Holtgrave et al., 2020; Yancy, 2020). Although studies of the COVID-19 pandemic are quickly accumulating, only a small portion have examined racial disparity in infection rates (Holtgrave et al., 2020; Yancy, 2020). Most of these studies have focused on relationships between socioeconomic (SES hereafter) or pre-existing chronic disease factors and racial disparity in SARS-CoV-2 infection rates (Abedi et al., 2020; Figueroa et al., 2020; Townsend et al., 2020). None of the studies have directly examined effects of green spaces. Evidence suggests that green spaces may have positive and independent effects on reducing the racial disparity in various long-term health outcomes (Lovasi et al., 2009; Mitchell & Popham, 2008; Payne-Sturges & Gee, 2006; Wolch et al., 2014). Yet, to our knowledge, there is no evidence to support green space's effect on reducing racial disparity in SARS-CoV-2 infection rates. This lack of knowledge may mean missing opportunities to slow down the COVID-19 pandemic, and to moderate future epidemics by urban greening. Our nationwide study is an initial ecological study aiming to establish a county-level relationship between black–white racial disparity in SARS-CoV-2 infection rates and the amount and type of green spaces in the United States.

* Corresponding author at: 614 Knowles Building, The University of Hong Kong, Pokfulam Road, Hong Kong Special Administrative Region.
E-mail address: jiangbin@hku.hk (B. Jiang).

https://doi.org/10.1016/j.envint.2021.106465
Received 27 November 2020; Received in revised form 8 February 2021; Accepted 9 February 2021
Available online 27 February 2021

1.1. A new trend: Significant environmental effects on racial disparity in health

Many studies have explored potential mechanisms that maintain and exacerbate general racial disparity in health outcomes to identify effective policies to address such inequities. Much of the racial disparity seems to be influenced by differences in SES, demographic, and pre-existing chronic disease factors (Abedi et al., 2020; Braveman et al., 2010; Singh & Yu, 2019; Townsend et al., 2020). Still, disparities remain significant after controlling for these factors. For example, life expectancy of black people is at least three years less than that of white people with a comparable income level, at every level of income (Braveman et al., 2010). Racial disparity is also pronounced in birth outcomes; for example, the infant mortality rate for college-educated black women is 2.5 times higher than that for college-educated white women (Singh & Yu, 2019). These studies suggest that persistent racial health disparities might be due, in part, to other types of systemic disparities between races.

After controlling for SES factors, an under-studied reason for racial disparity in health outcomes is built environment disparity (Popescu et al., 2018; Wolch et al., 2014). People of different races, especially black and white people in the United States, have lived in neighborhoods with distinct environmental qualities (Massey, 2001). Predominantly black neighborhoods have, on average, fewer green spaces for physical activity, lower accessibility to healthy food, and lower safety from traffic and crime (Lovasi et al., 2009; Phelan & Link, 2015; Wen et al., 2013; Williams & Sternthal, 2010). These findings have prompted researchers across disciplines to shift from investigating exclusively social, economic, and educational interventions, to investigating physical environmental interventions as a means to alleviate persistent racial disparities (Lovasi et al., 2009; Mitchell & Popham, 2008; Phelan & Link, 2015; Williams & Sternthal, 2010).

1.2. Positive effects of green spaces on human health

The significantly positive effects that green spaces have on human health have drawn considerable attention from researchers, public health professionals, and governmental officers over the past decades. A growing number of studies have measured these effects at the regional (Mitchell & Popham, 2008), municipal (Lu, 2019), neighborhood (Sullivan et al., 2004), and site scales (Jiang et al., 2014). Green spaces influence human health through several major pathways (Hartig et al., 2014; Markevych et al., 2017): improved cognitive performance and reduced mental fatigue (a mental state with a deficit of directed attention) (Jiang et al., 2021; Jiang et al., 2018; Kaplan, 1995), reduced impulsiveness and aggressiveness and enhanced self-discipline (capability of accepting delayed gratification and controlling impulse (Kuo & Sullivan, 2001a, 2001b; Kuo & Taylor, 2004; Taylor et al., 2002a, 2002b), reduced mental stress (Jiang et al., 2014; Ulrich et al., 1991), increased physical activity (Cohen et al., 2007; Lu et al., 2018; Pretty et al., 2005), increased social activity and social capital (Holtan et al., 2014; Coley, Sullivan, & Kuo, 1997), and by providing ecological benefits such as air and water purification (Bolund & Hunhammar, 1999). These pathways have been demonstrated across different geographic, social, and cultural contexts (Bratman et al., 2012; Hartig et al., 2014; Jiang et al., 2015).

1.3. Green spaces reduce racial disparity in health: Circumstantial evidence and knowledge gaps

A few studies have explored how green spaces can mitigate health disparities among populations with different SES. A nationwide study in the UK revealed that the association between income level and all-cause mortality and circulatory disease mortality at the neighborhood scale is moderated by the amount of green space in a neighborhood (Mitchell & Popham, 2008). Exposure to green space reduces health disparities among people of different SES. Another study reported that the supply of public green spaces reduces the health disadvantages due to obesity and obesity-related illnesses in residents of low SES by encouraging physical exercise (Lovasi et al., 2009). These studies explore SES disparity, rather than racial disparity, though SES and racial disparities are often correlated (Williams et al., 2016).

A study of 496 of the most populated cities in the U.S. found that cities with higher median incomes and lower percentages of Latino and non-Hispanic black residents had greater access to park spaces than their counterparts in majority-non-Hispanic white communities (Browning & Rigolon, 2018). This suggests green space may play a role in mitigating health disparities among people of different races. To be clear, however, this study did not examine within-city racial differences in health outcomes.

Taken together, these studies provide strong evidence that green spaces may mitigate racial disparities in health outcomes which may make the findings are vulnerable to be distorted by significant social, cultural, governmental regulation differences between cities, yet none of them explored the extent to which green spaces mitigate health disparities in rates of communicable disease, such as SARS-CoV-2. This critical gap in knowledge prevents us from developing equitable environmental design solutions to promote public health during the COVID-19 pandemic and future health crises.

1.4. Hypothesis

We hypothesize that the supply of green spaces can moderate racial disparities in SARS-CoV-2 infection rates. We predict that the black–white racial disparity in the U.S. SARS-CoV-2 infection rates is significantly lower in areas with a higher ratio of green space.

2. Methods

2.1. Study design

We compared the black–white disparity in SARS-CoV-2 infection rates in populations living in urbanized counties of the United States that have different amounts of green spaces, while adjusting for potential confounding factors of these counties. The infection data were retrieved on July 10, 2020. We adopted a within-subject (within-county) research design with a representative sample across the country. Black–white disparity was measured as the difference in the infection rate of black and white individuals in the same county. This allowed us to largely remove the bias caused by between-subject (between-county) factors that may lead to the uneven spread of SARS-CoV-2 in different counties, such as the distance to COVID-19 epicenters, climate, or local government policies.

2.1.1. Study areas

The United States is among the countries most severely impacted by COVID-19. It also has severe black–white racial inequalities in SARS-CoV-2 infection rates. Our study used counties as the basic unit of analysis, which are the fundamental administrative unit in the United States. There are a total of 3,142 counties or county-equivalent areas in the United States.

The most urbanized counties were chosen because we assumed that the racial inequality in the SARS-CoV-2 infection rates is more pronounced in denser urban environments. First, we identified a list of 314 large cities with a population $\geq$ 100,000 in 2019. Second, we identified a total of 229 counties containing or overlapping these large cities. Third, counties without infection data for black and white people were excluded. A total of 135 counties were chosen as our study areas. The total population in these counties was 132,350,027, which comprised 40.3% of the total population in the United States. The large population size in our study areas ensures the generalizability of potential findings. We chose counties rather than cities as the unit of analysis because the

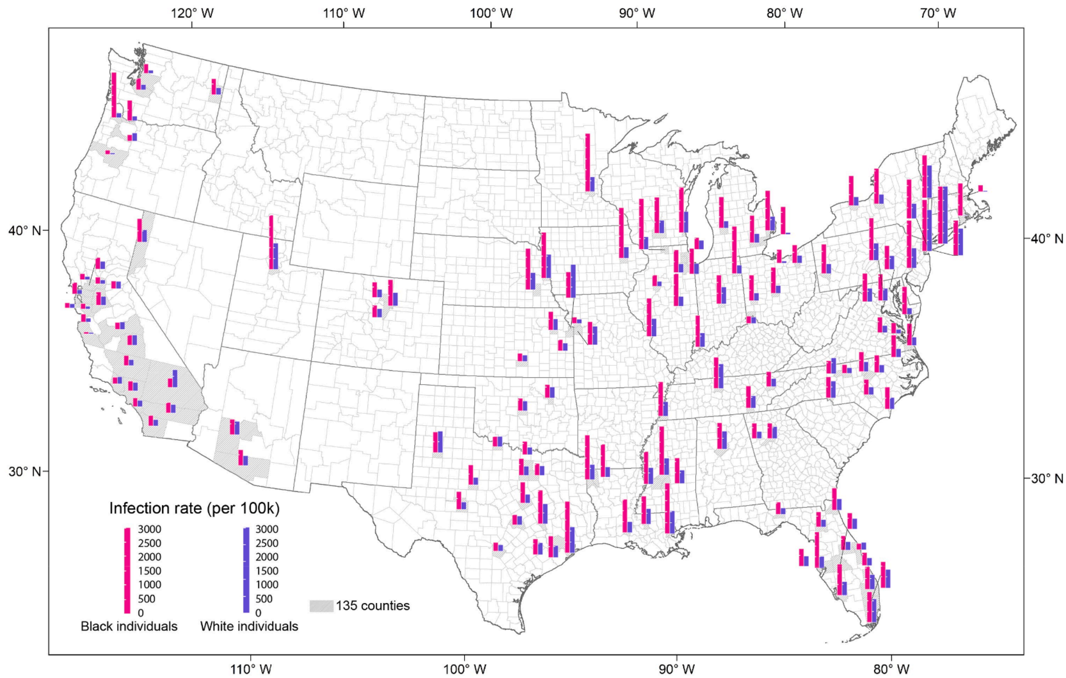

Fig. 1. SARS-CoV-2 infection rates of black and white individuals in the 135 most urbanized counties of the United States. The pink columns indicate infection rates for black people, while the blue columns indicate infection rates for white people. The height of the columns indicates the magnitude of the infection rate. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

infection data for black and white individuals were often unavailable at the city or neighborhood level.

2.1.2. SARS-CoV-2 infection rates

The infection data were collected from the county health department portals on July 10, 2020. Only SARS-CoV-2 infections in black and white individuals were collected in this study. We calculated the SARS-CoV-2 infection rates for black and white people (numbers of cases per 100 k) based on the total white and black populations in each county, respectively, which were retrieved from the 2019 census data (United States Census Bureau, 2020). The racial disparity in the SARS-CoV-2 infection rates was calculated as the difference between the infection rate in black individuals and the infection rate in white individuals in the same county.

2.1.3. Green spaces

We used three datasets to assess green spaces, namely the National Land Cover Datasets in 2016 (Yang et al., 2018), the Tree Canopy Cover Datasets of the United States Forest Service (USFS), and the normalized difference vegetation index (NDVI).

Based on Landsat imagery at 30-meter resolution, the NLCD 2016 provides spatially explicit and reliable land-cover classification, identifying different types of land cover such as forest, wetland, grassland, and built area (Yang et al., 2018). The overall agreement between different land-cover classifications and the reference data ranges from 71% to 97% (Yang et al., 2018). The NLCD 2016 has 16 types of land cover. We considered the following land-cover types with dominant natural elements: developed open space, deciduous forest, evergreen forest, mixed forest, shrub and scrub, grassland and herbaceous, pasture and hay, cultivated crops, woody wetlands, and emergent herbaceous wetlands (Appendix Table 2). Deciduous, evergreen, and mixed forest categories were merged into a combined "forest" land-cover category. The ratio of these green spaces over the total county area was calculated.

The Tree Canopy Cover Dataset was derived from the NLCD by the USFS. It provides estimates of the percent tree canopy cover at 30-meter resolution. We aggregated the total tree-canopy cover estimates for each county and then divided it by the county area.

The NDVI is a widely used index that measures the quantity of green vegetation cover at the pixel level via remote sensing. We obtained the NDVI at a 30-meter resolution from the Google Earth Engine, which integrates Landsat 8 imagery in its cloud platform (Gorelick et al., 2017). Four pixel-level average values were calculated for each county in each month from March to July in 2020. We obtained the mean of four monthly NDVI values as a proxy for overall green space coverage during the research period.

We found that the land-cover dataset had high multicollinearity with the two other measurements of green spaces. For instance, the NDVI and forest land-cover are strongly correlated (Pearson correlation coefficient: $r = 0.64$, $p < 0.001$), as are tree canopy and forest ($r = 0.85$, $p < 0.001$). Therefore, we only used measures from the land-cover dataset.

2.1.4. Confounding factors

Previous studies have shown that demographic and SES characteristics are important predictors of SARS-CoV-2 infection risk or racial disparity in this risk (Abedi et al., 2020; Figueroa et al., 2020). From the 2019 census data, we obtained the following county level data for the selected 135 counties: population density, the female population ratio, the difference in black–white population, the difference in black–white older adults, household size, housing value, rate of population with a high school diploma or higher, rate of households with broadband, median household income, poverty rate, healthcare receipts data, travel time to work, employment rate, and the number of firms (Appendix Table 1) (United States Census Bureau, 2019, 2020).

Pre-existing chronic disease is another factor that may influence the racial disparity in SARS-CoV-2 infection rates (Townsend et al., 2020). County-level pre-existing chronic disease factors were collected from the 2016–2018 interactive heart disease and stroke data collated by the Centers for Disease Control and Prevention (Centers for Disease Control and Prevention, 2020a, 2020b). The pre-existing chronic disease factors that we used were the coronary heart disease death rate, the heart failure death rate, the diagnosed diabetes rate, and the obesity rate for each county (Appendix Table 1).

The dominant land-cover types in the built-up areas of each county were also considered because they represent the level of urbanicity of

Table 1
Descriptive statistics for SARS-CoV-2 infection rates, SES and demographic factors, pre-existing chronic disease factors, and green space factors in the USA's 135 most urbanized counties.

Variable Categories	Variables	Min	Max	Mean	SD	Unit or Formula	VIF Test
Infection outcomes	Black infection rate	91.6	2514.8	987.9	583.7	Cases per 100 k	N/A
	White infection rate	29.1	2486.2	496.8	336.2	Cases per 100 k	N/A
	Difference in black–white infection rates	−367.9	1874.2	491.1	447.3	Cases per 100 k	N/A
SES and demographic factors	Population density	27.8	19625.8	1003.2	2356.6	Persons per square kilometer	Retained
	Female population ratio	0.479	0.533	0.511	0.010	Female/ total population	Retained
	Difference in black–white population	−0.878	0.481	−0.407	0.274	Black-to-white population ratio	Retained
	Difference in black–white older adults	−0.201	0.050	−0.078	0.041	Black older adults-to-white older adults population ratio	Retained
	Household size	2.1	3.3	2.6	0.3	Persons per household	Retained
	Households with broadband	0.666	0.917	0.818	0.056	Ratio	Retained
	Median household income	38085	117374	62484	16126	USD	Retained
	Healthcare receipts	222956	2129326	771836	310816	1000 USD per 100 k	Retained
	Number of firms	5000	19365	8595	2076	Number of firms per 100 k	Retained
	Housing value	95600	1009500	265468	181861	USD	Removed
	Rate of high school graduate or higher	0.698	0.959	0.882	0.049	Ratio	Removed
	Poverty rate	0.042	0.273	0.139	0.046	Ratio	Removed
	Travel time to work	15.50	44.80	25.61	5.50	Minutes	Removed
	Employment rate	18309	139791	43397	15190	Employment per 100 k	Removed
Pre-existing chronic disease factors	Coronary heart disease death rate	45.3	144.9	85.1	22.0	Cases per 100 k	Retained
	Heart failure death rate	34.4	170.3	89.1	24.6	Cases per 100 k	Retained
	Diagnosed diabetes rate	0.046	0.140	0.090	0.018	Cases/total population	Retained
	Obesity rate	0.147	0.401	0.284	0.057	Cases/total population	Removed
Green space factors	Developed open space	0.005	0.289	0.102	0.064	Developed open space area/ county area	Retained
	Forest	0.001	0.738	0.172	0.163	Forest area/county area	Retained
	Shrub and scrub	0.000	0.829	0.082	0.177	Shrub and scrub area/county area	Retained
	Grassland and herbaceous	0.001	0.498	0.061	0.093	Grassland and herbaceous area/county area	Retained
	Pasture and hay	0.000	0.485	0.069	0.092	Pasture and hay area/county area	Retained
	Cultivated crops	0.000	0.719	0.124	0.168	Cultivated crops area/county area	Retained
	Woody wetlands	0.000	0.453	0.050	0.078	Woody wetlands area/county area	Retained
	Emergent herbaceous wetlands	0.000	0.605	0.026	0.080	Emergent herbaceous wetlands area/county area	Retained
Built-up area factors	Developed Low Intensity	0.008	0.414	0.118	0.086	Developed Low Intensity area/county area	Removed
	Developed Medium Intensity	0.006	0.367	0.093	0.085	Developed Medium Intensity/county area	Removed
	Developed High Intensity	0.001	0.505	0.052	0.081	Developed High Intensity/county area	Removed

Note: Min = minimum; Max = maximum; SD = standard deviation; Per 100 k = Per 100,000 population; USD = United States Dollar.

each county. Three land-cover types of built-up area from NLCD 2016 were included: developed low intensity, developed medium intensity, and developed high intensity (Appendix Table 2). The ratio of these built-up areas over the total county area was calculated.

2.2. Statistical analysis

Three statistical analysis steps were performed. First, a paired *t*-test was used to examine whether there was a significant difference between SARS-CoV-2 infection rates in black and white people in the same county. Second, a variance inflation factor (VIF) test was used to remove potential multicollinearity among the independent variables. All of the factors with a VIF ≥ 4 were excluded from our models (O'brien, 2007) (Appendix Tables 1 & 2).

Third, hierarchical linear-regression models were used to examine the associations between the black-white differences in SARS-CoV-2 infection rates and green space factors, while controlling for other confounding factors. The first model (Model 1) included the SES and demographic factors only. The second model (Model 2) included these factors as well as the pre-existing chronic disease factors. The last model (Model 3) included green space factors and built-up area factors in addition to all factors of Model 2.

All of the analyses were performed using R v4.0.2 with built-in 'lm' function (R Core Team, 2020). The model R^2 values, adjusted R^2 values, standardized coefficient (β) values, 95% confidence intervals, and *p*-values were reported.

3. Results

Results are presented in three sections. First, we present the incidence of SARS-CoV-2 infections in the sample of 135 most urbanized counties in the United States and examine the extent to which there are differences in infection rates among black and white populations. Second, we report demographic and green space characteristics of the sampled counties. Third, we employ hierarchical linear modeling to examine the extent to which, after controlling for SES, demographic, pre-existing chronic disease, and built-up area factors, the ratio of green spaces are associated with black-white disparities in SARS-CoV-2 infection rates. Finally, we report four green space factors that have significant negative associations with racial disparity in SARS-CoV-2 infection rates.

3.1. Does a racial disparity in infection rates exist?

As of July 10, 2020, there were a total of 1,425,461 cases of SARS-CoV-2 infection in the 135 most urbanized counties in the United States, which accounted for 47% of the total cases of infection (3,038,325) in the United States (Fig. 1). The 135 most urbanized counties were selected because they contain or overlap with 314 large cities with a population ≥ 100,000 in 2019 (see details in Methods). The county-level average infection rate for white individuals was 497 persons per 100,000 population, whereas the infection rate for black individuals was approximately twice this (988 persons per 100,000 population) (Fig. 1 & Table 1). The average black-white difference in the infection rate was 447 persons per 100,000 population. White

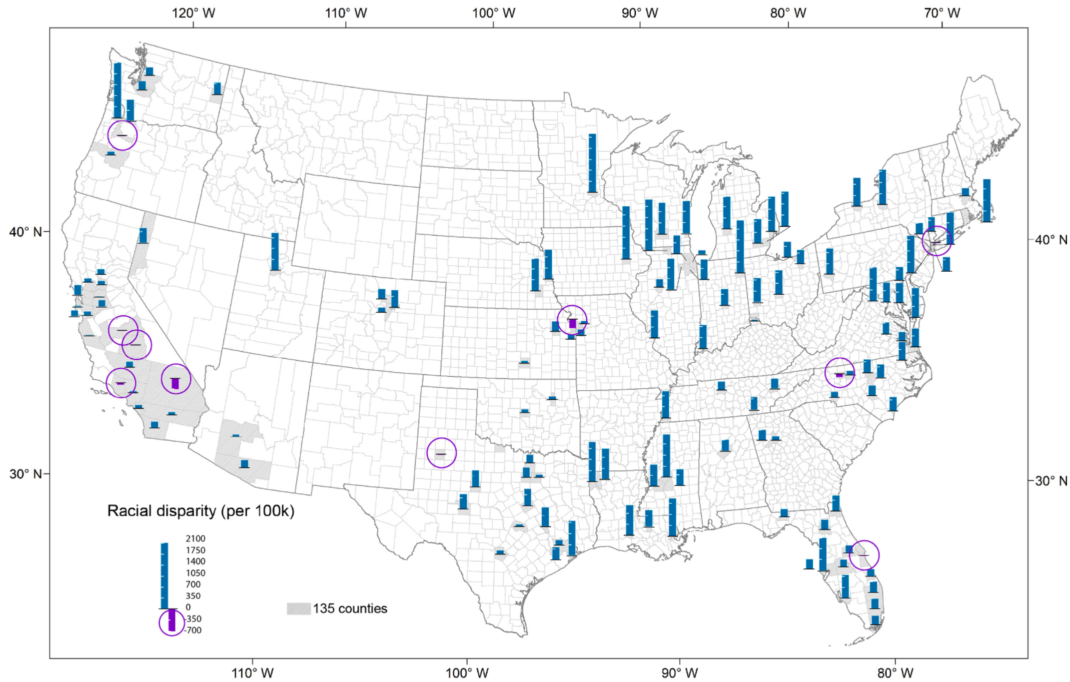

Fig. 2. Racial disparity in the SARS-CoV-2 infection rates between black and white individuals in the 135 most urbanized counties of the United States. The cyan column indicates black infection rate is higher than white; the purple column (with circle) indicates white infection rate is higher than black. The height of the columns indicates the magnitude of disparity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

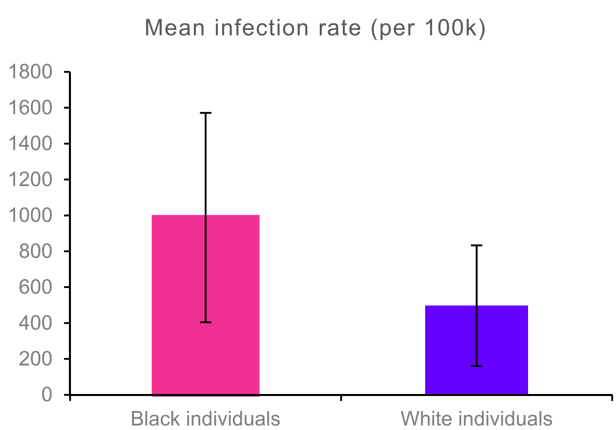

Fig. 3. The mean SARS-CoV-2 infection rate of black individuals is approximately twice that of white individuals (988 vs. 497 per 100,000 population). Significant at $p < 0.001$ using a paired t-test. The error bar represents standard deviation.

individuals had a higher infection rate than black individuals in only 11 out of the 135 counties (Fig. 2). As expected, a paired t-test revealed that the difference in infection rates between black and white people is significant, with $t\ (134) = 12.757$ and $p < 0.001$ (Fig. 3).

3.2. Characteristics of the sampled counties

Table 1 shows that there are proportionally more white than black people in the study areas, which is consistent with the overall racial composition in the United States. The sample includes an average of 2.6 persons per household and a notably large range in median household income across counties. In terms of the green space factors, the sample includes a high quantity of developed open space and forest cover (Fig. 4), and low levels of shrub and scrub, and grassland and herbaceous cover. Fig. 4 shows the ratio of four types of green space in each county.

3.3. Modeling association of green spaces and infection disparity

By fitting three hierarchical regression models, we identify three relevant associations (Table 2). Model 1 shows that SES and demographic factors have a significant association with racial disparity in the SARS-CoV-2 infection rate across the 135 counties (adjusted R^2 of 0.12, $p = 0.003$). We also note that there is a significantly negative association between household size and racial disparity in SARS-CoV-2 infection rates, such that as average household size increases, infection disparity falls.

After adding pre-existing chronic disease factors into Model 2, the explanatory power of Model 2 slightly decreases (adjusted $R^2 = 0.11$, $p = 0.007$). Model 2 shows that the combination of SES, demographic, and pre-existing chronic disease factors is associated with racial disparity. However, the overall statistical significance of Model 2 was not substantially better than that of Model 1 ($p = 0.430$ for the sum-of-squares difference).

After adding green space factors into Model 3, the overall explanatory power of Model 3 increased by 18% (adjusted $R^2 = 0.29, p < 0.001$). Model 3 reveals that four green space factors are independently negatively associated with racial disparity. These are: land-cover ratio of developed open space; forest; shrub and scrub; and grassland and herbaceous. In addition, household size is negatively associated with SARS-CoV-2 infection rate disparity between races, while death from heart failure rate is positively associated with it.

To improve our understanding of the associations between the four green spaces and racial disparity in SARS-CoV-2 infection rates, we plotted the independent effects of the four types of green spaces in Model 3 after controlling for other factors (using the 'effects' package of the statistical software R (Fox & Weisberg, 2018). Fig. 5 clearly demonstrates the negative relationships between the proportion of the four types of green space and the racial disparity in SARS-CoV-2 infection rates.

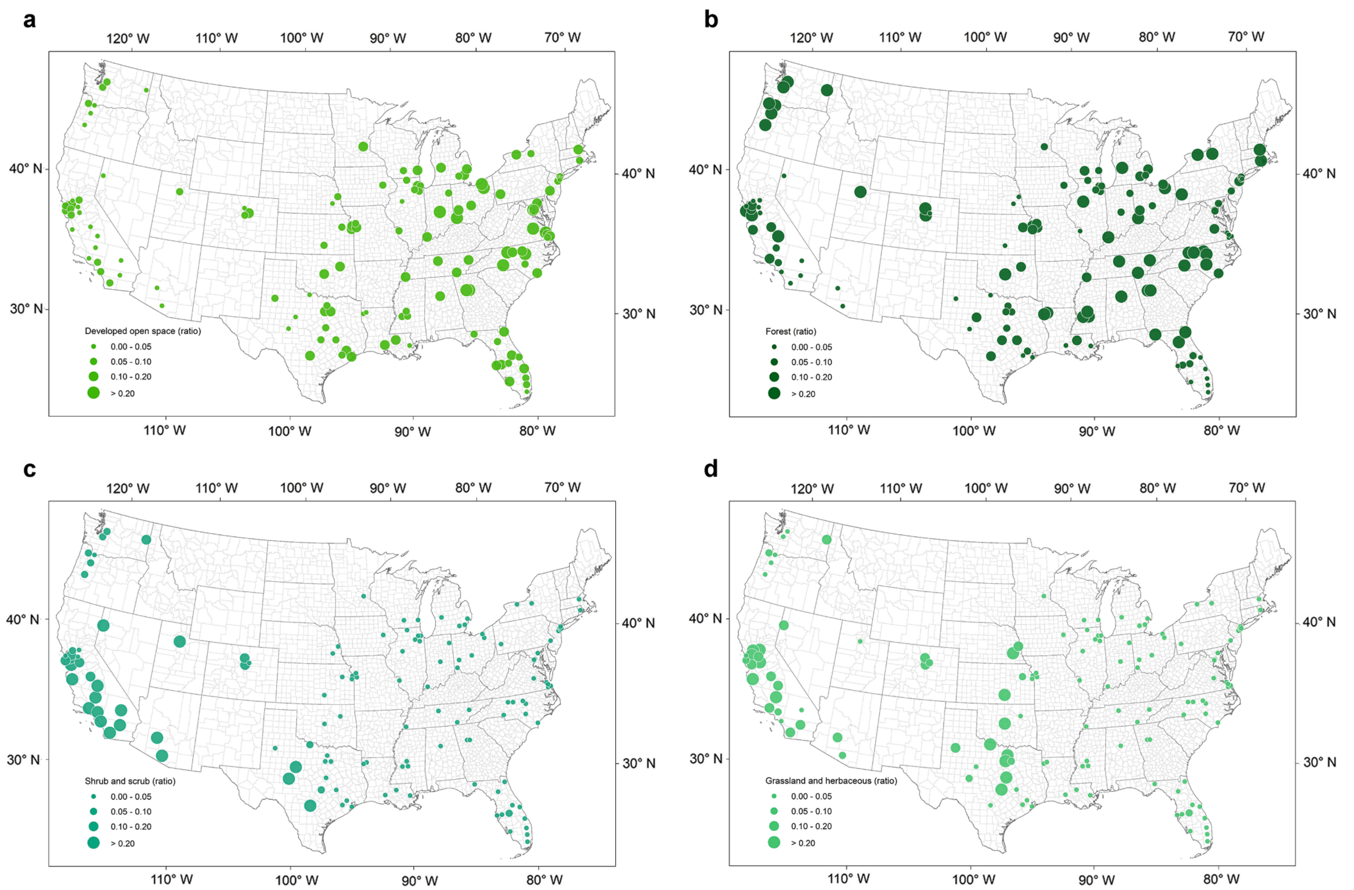

Fig. 4. Ratio of four types of green space to total county area, by county. a developed open space. **b** forest. **c** shrub and scrub. **d** grassland and herbaceous. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Three hierarchical linear regression results ($N = 135$).

Model Predictors	Model 1		Model 2		Model 3	
	β (95% CI)	***p*-value**	**β (95% CI)**	***p*-value**	**β (95% CI)**	***p*-value**
Population density	−0.02 (−0.22, 0.18)	0.860	0.02 (−0.21, 0.24)	0.884	−0.14 (−0.38, 0.11)	0.279
Female population ratio	0.06 (−0.15, 0.27)	0.552	0.10 (−0.12, 0.31)	0.362	0.06 (−0.15, 0.28)	0.558
Difference in black–white population	−0.03 (−0.25, 0.19)	0.782	−0.03 (−0.25, 0.20)	0.812	0.03 (−0.20, 0.25)	0.801
Difference in black–white older adults	−0.12 (−0.31, 0.08)	0.232	−0.13 (−0.32, 0.07)	0.210	−0.17 (−0.36, 0.02)	0.079
Household size	−0.42 (−0.65, −0.19)	<0.001***	−0.42 (−0.65, −0.18)	<0.001***	−0.37 (−0.61, −0.14)	0.002**
Households with broadband	−0.15 (−0.42, 0.12)	0.276	−0.11 (−0.39, 0.18)	0.467	−0.07 (−0.34, 0.20)	0.611
Median household income	0.17 (−0.10, 0.44)	0.221	0.20 (−0.09, 0.49)	0.168	0.23 (−0.04, 0.50)	0.095
Healthcare receipts	−0.02 (−0.24, 0.20)	0.866	−0.04 (−0.26, 0.19)	0.751	−0.01 (−0.23, 0.22)	0.963
Number of firms	0.02 (−0.18, 0.21)	0.873	0.04 (−0.18, 0.25)	0.744	0.01 (−0.23, 0.25)	0.915
Coronary heart disease death rate			0.06 (−0.15, 0.27)	0.557	0.01 (−0.19, 0.21)	0.907
Heart failure death rate			0.14 (−0.06, 0.35)	0.175	0.26 (0.04, 0.48)	0.020*
Diagnosed diabetes rate			−0.04 (−0.29, 0.21)	0.760	−0.07 (−0.32, 0.18)	0.578
Developed open space					−0.31 (−0.56, −0.07)	0.011*
Forest					−0.31 (−0.53, −0.09)	0.006**
Shrub and scrub					−0.32 (−0.56, −0.07)	0.012*
Grassland and herbaceous					−0.42 (−0.62, −0.22)	<0.001***
Pasture and hay					−0.12 (−0.30, 0.06)	0.180
Cultivated crops					0.01 (−0.23, 0.25)	0.947
Woody wetlands					0.01 (−0.18, 0.19)	0.963
Emergent herbaceous wetlands					−0.09 (−0.30, 0.13)	0.430
R^2/AdjustedR^2	0.178/0.119	0.003**	0.193/0.113	0.007**	0.294/0.288	<0.001***
ANOVA F-statistic of R^2change			0.927 (vs. Model 1)	0.430	4.739 (vs. Model 2)	<0.001***

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

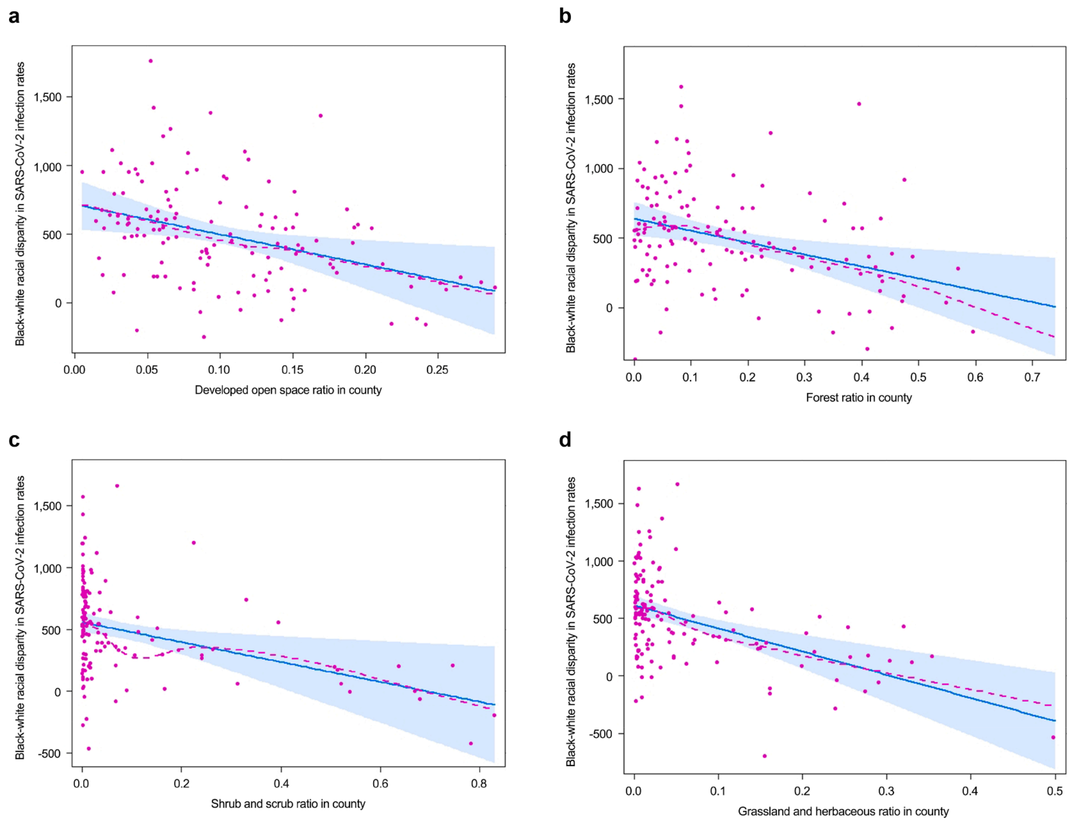

Fig. 5. Individual effects of the ratio of four green spaces on the black–white racial disparity in SARS-CoV-2 infection rates (in Model 3, with non-greenspace predictors fixed). a developed open space. **b** forest. **c** shrub and scrub. **d** grassland and herbaceous. Shaded areas represent the pointwise 95% confidence interval. Points represent partial residuals. Straight line represents the linear fitting of the effects. Dashed line represents the progressive fitting of the effects. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

In this study of 135 urbanized counties in the United States, we found a large and statistically significant disparity in infection rates of the SARS-CoV-2 virus for black and white populations. Using hierarchical linear modelling, we found that the combination of SES, demographic, and pre-existing chronic disease conditions explained about 11% of variance in racial disparity. Green spaces explained an additional 18% of the variance. Four types of green spaces were significantly, negatively associated with the racial disparity in SARS-CoV-2 infection: open space in developed areas, forest, shrub and scrub, and grassland and herbaceous.

In the paragraphs that follow, we consider possible mechanisms through which greater amounts of green spaces within a county might contribute to a reduction in racial disparity in SARS-CoV-2 infection rates. The plausible mechanisms are supported by theoretical and empirical evidence. We discuss the contributions of our findings and identify questions for future research. To our knowledge, this is the first study to find that green space factors have significant independent effects on the racial disparity in COVID-19 infection rates.

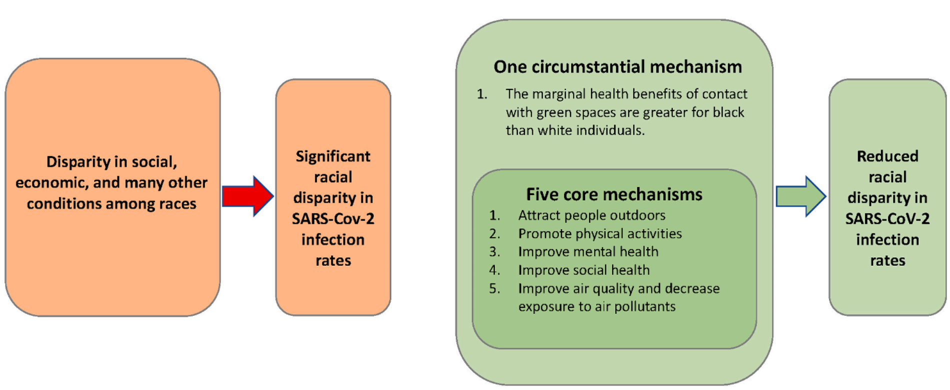

Fig. 6. By what set of conditions are the racial disparities in SARS-CoV-2 infection rates reduced? Evidence suggests that disparities in social, economic, and many other conditions among races leads to significant differences in SARS-CoV-2 infection rates between black and white populations. We found that the proportion of green spaces in a county was negatively related to differences between SARS-CoV-2 infection rates: The greater the proportion of green space, the less black-white disparity in infection rates. We posit five core mechanisms and one circumstantial mechanism to interpret why a high ratio of green spaces at the county scale is associated with a lower racial disparity in SARS-CoV-2 infection rates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.1. Interpretation of key findings: Theoretical mechanisms

There is growing evidence that the dominant pathway for transmission of the SARS-CoV-2 virus is through aerosol particles (Klompas et al., 2020; Zhang et al., 2020). That is, the primary route of transmission is via virus-containing droplets and aerosols exhaled from infected individuals as they breathe, speak, sing, cough, or sneeze. In indoor settings that lack adequate ventilation, the virus can concentrate in the air, which facilitates its spread. In outdoor settings, the likelihood of contracting the virus is greatly reduced, due to increased air movement and the ease of social distancing (Leclerc et al., 2020). We interpret the findings presented above in light of the understanding that the primary pathway of transmission of the SARS-CoV-2 virus is through aerosol particles.

In this study, we found, after controlling for potential confounding factors, that greater proportions of open space in developed areas, forest, shrub and scrub, grassland, and herbaceous landscapes were each significantly, negatively correlated with the size of discrepancy in black-white infection rates. In urban counties with more green spaces available, the racial disparity in SARS-CoV-2 infection rates was lower than in counties that had less available green space.

How might we account for these findings? We propose a theoretical model with four core mechanisms and one circumstantial mechanism that may account for the observed relationships (Fig. 6).

4.1.1. Five core mechanisms

First, and perhaps most likely, is that green spaces are socio-pedal – that is, they attract people outdoors. A study in Chicago found that individuals using spaces immediately outside apartment buildings were much more likely to be in relatively green spaces than in relatively barren spaces (Coley et al., 1997). A follow-up study of outdoor urban spaces found on average 90% more people used green than barren neighborhood spaces (Sullivan et al., 2004). Another study reported that urban residents dislike and fear urban neighborhood spaces when they are devoid of vegetation, but that the simple addition of trees and grass was sufficient to transform outdoor common spaces from a space they liked *not at all*, to a space they liked *quite a lot* or *very much* (Kuo et al., 1998).

These findings suggest that green neighborhood spaces attract people outdoors. Being outdoors reduces the spread of the virus through three pathways. First, compared to the indoor air movement, outdoor air movement disperses the virus to a low level that is much less infectious. Second, green spaces do not only encourage people to visit outdoors more frequently, but also encourage people to spend longer time outdoors (Braubach et al., 2017). In other words, access to green spaces can reduce portion of wake time people spend in the indoor environments for socializing thus are exposed to less virus than they might otherwise be. Third, it is easier to maintain a safe social distance outdoors (Leclerc et al., 2020). To the extent that black individuals have disproportionately less access to green spaces than their white counterparts (Phelan & Link, 2015; Wen et al., 2013; Williams & Sternthal, 2010), simply having access to green spaces that pull people outdoors is likely to reduce the racial disparity in infections rates we reported above.

Second, counties with larger portions of green spaces are more likely to provide residents of all racial groups greater access to green spaces, thus promoting physical activity before and during the pandemic (Cohen et al., 2007; Lovasi et al., 2009; Lu et al., 2018; Pretty et al., 2005). Physical activity may have enhanced county residents' immune system regardless of race and moderated factors behind race-based infection disparities (Rook, 2013; Shi et al., 2020). Physical activity conducted in nature provides additional benefits compared with physical activity conducted in indoor environments (Pretty et al., 2005). Here again, the disproportionate lack of access to green spaces that many black people live with is likely to explain some of racial disparity in infection rates. Black individuals who have access to open green spaces may accrue health benefits from conducting physical activity in these green spaces, and therefore potentially have lower infection rates compared to black people who cannot access open green spaces.

Third and fourth , proportionately more green spaces in a county may result in enhanced mental (Bratman et al., 2012) and social health (Taylor et al., 2002a, 2002b) before and during the pandemic, regardless of race, thus moderating risks that would otherwise fall more heavily on black communities. There is strong evidence that black people in the U. S. experience greater stress burdens than white people (Lovasi et al., 2009; Payne-Sturges & Gee, 2006), and this disparity may be especially profound during the pandemic. Visual or physical contact with urban green spaces can reduce mental fatigue (Jiang et al., 2018), reduce mental stress (Chang et al., 2021; Jiang et al., 2014; Ulrich et al., 1991), and enhance self-discipline and reduced impulsiveness (Kuo & Taylor, 2004; Taylor et al., 2002a, 2002b) at the individual level. Such exposure to green spaces can also reduce negative moods (Brooks et al., 2017; Jiang et al., 2020) and verbal and behavioral aggressiveness (Branas et al., 2018; Kuo & Sullivan, 2001a, 2001b), which can lead to enhanced trust and collaboration (Arnberger & Eder, 2012). Taken together, these benefits of exposure to nature can promote immune system health (Rook, 2013; Shi et al., 2020) and social cohesion which may provide protective benefits against the virus.

Lastly, more green spaces may decrease the SARS-CoV-2 infection risk by improving air quality and decreasing exposure to air pollutants (e.g., $PM_{2.5}$) that might contribute to a higher SARS-CoV-2 infection rate (Zhu et al., 2020). Black households tend to be found in higher density, more polluted streets, compared with white households (Massey, 2001; Phelan & Link, 2015; Wen et al., 2013; Williams & Sternthal, 2010). Studies have shown that air quality in high-density residential areas in urban neighborhoods is significantly worse than in suburban and rural residential areas (Nowak et al., 2014). More green spaces in or near the urban centers where black communities live may improve air quality (Mitchell & Popham, 2008; Wolch et al., 2014), thereby contributing to lower racial disparity in SARS-CoV-2 infection rates. However, the supply the green spaces in urban centers is insufficient to provide healthy air for the entire urban region (Richardson et al., 2012). The large-scale greening of surrounding areas is critical to achieving this goal (Doughty & Hammond, 2004).

4.1.2. One circumstantial mechanism

These findings suggest that greater proportions of green spaces in a county make it more likely that black and white individuals have more equal access to the health benefits of green spaces. This, we suggest, is a crucial mechanism explaining our regression findings: Other things being equal, an increase in the quantity or accessibility of green spaces in an urban area might be expected to have an equal effect on black and white households (Chiabai et al., 2020; Webster, 2010; Wolch et al., 2014). Black households, however, are less likely to have access to green spaces than white households. Thus, the marginal health benefits to black households resulting from more green spaces will be greater than for whites. This difference of marginal effects can be regarded as the circumstantial mechanism to support the impacts of four core mechanisms (Fig. 6).

4.2. Contributions and implications

This study makes theoretical and practical contributions which can influence future research, policymaking, and urban design in four major ways.

First, this study is an initial effort to measure whether and to what extent green spaces within and beyond developed urban areas are associated with racial disparities in rates of contagious disease infection. Although a few studies have identified some built environment factors that are related to racial disparity in SARS-CoV-2 infection rates (e.g., crowded living conditions, staying in senior living communities, and dense urban areas) (Evans, 2020; Khunti et al., 2020; Rozenfeld et al., 2020; Tai et al., 2020), none have addressed the association of access to green spaces and health outcomes.

Second, this study employed a within-subject research design with a standard spatial sampling unit across the country, providing a representative sample of U.S. urbanized counties. In contrast with previous studies on COVID-19 that examined SARS-CoV-2 infection or mortality rates across counties or cities (Abedi et al., 2020; Figueroa et al., 2020), our study focused on comparing difference in SARS-CoV-2 infection rates among white and black people in the same county. By comparing racial disparity in infection rates within each county we obtain greater statistical validity, mitigating bias caused by uneven spread of infections across counties due to differences in national road network accessibility, airports and railway connectivity, governmental regulations, social norms, quantity and quality of healthcare services, and many other factors.

Third, this study suggests that green spaces, as a critical infrastructure (Coutts & Hahn, 2015; Hartig et al., 2014; Jiang et al., 2020; Markevych et al., 2017; Suppakittpaisarn et al., 2019; Suppakittpaisarn et al., 2017; Yu et al., 2006), may be considered a relevant intervention to reduce the racial disparity of infectious diseases with characteristics similar to the current pandemic. If evidence from this study is confirmed by future studies, we suggest that providing an adequate supply of accessible and well-designed green spaces in urban areas, and preserving and developing natural green spaces across counties, should be incorporated into epidemic and pandemic resilience strategies for highly urbanized areas. Considering that urban and agricultural areas are rapidly encroaching on forest, grassland, and many other natural landscapes inside and/or outside cities worldwide (Irwin & Bockstael, 2007), it is crucial to maintain and increase efforts to preserve scarce urban green spaces. This approach may also be expected to deliver health and racial equity outcomes, as well as environmental outcomes.

Fourth, this study may shed light on the impacts of other environmental features that may reduce the racial disparity in health outcomes. While our study explored the association between higher ratio of green spaces and lower racial disparity in SARS-CoV-2 infection rates, other studies might explore how the provision of grocery stores, health care facilities, or public transportation options is associated with reduced racial disparity in infection rates.

4.3. Limitations and opportunities for future research

This study has some limitations that point to opportunities for future research.

We collected SARS-CoV-2 infection data from government websites in each of the 135 counties we examined. The number of confirmed cases in some areas in the US may be underestimated due to under-testing, although the bias caused by the different levels of access to testing can be largely mitigated by the with-in county method (Wu et al., 2020). Moreover, it is possible that there is significant racial disparity in SARS-CoV-2 testing rates in the USA (Mody et al., 2020): The black-white racial disparity of infection rates might be even higher than that reported in this study if black individuals have a lower level of access to testing than white individuals. The future studies should consider and make a stronger control of these confounding factors.

Moreover, although there are 229 counties containing or overlapping all cities with a population $\geq$ 100,000 in the United States, infection data were unavailable for 94 of these counties. In addition, the spatial reach of the counties was often larger than the spatial reach of the corresponding cities, as counties contain both cities and surrounding undeveloped areas. Researchers should investigate the association between green space and racial disparity in infection rates at a fine-grained spatial scale, such as at a city or neighborhood scale, when data are available.

In this study, we assessed the ratio of green spaces by land-cover type in each county. However, racial disparity in accessing green spaces is likely to exist within each county. Previous studies suggest that black communities have access to fewer parks than white communities. Accessible parks in black communities often have fewer amenities, are poorly maintained, and are perceived as less safe (Carlson et al., 2010; Rigolon, 2016). Future studies should investigate the racial inequities in access to green spaces and quality of green spaces.

This study only examined racial disparities in SARS-CoV-2 infection rates in the U.S.. While the racial disparity in infection rates in the U.S may be similar to other countries with diverse racial populations (Figueroa et al., 2020; Webb Hooper et al., 2020; Yancy, 2020), we suggest that this research be replicated in other countries to fully determine the complex issue of racial disparity in infection rates in relation to environmental exposure and pandemic dynamics.

Lastly, this study provides a baseline analysis of green spaces and racial disparity in pandemic infections. It is limited by the normal constraints of a cross-sectional, ecological design. Cross-sectional associations do not imply causality and we cannot fully avoid the possibility of ecological fallacy. These are possibilities that can be investigated in further studies. Nevertheless, results from this study echo findings of many studies that report causal links between more green spaces, better health status and lower health disparities.

5. Conclusion

This study was an initial effort to understand the relationships between environmental factors and racial disparity in SARS-CoV-2 infection rates. We employed a hierarchical regression analysis to perform within-county comparisons of infection rates for black and white individuals. After controlling for SES, demographic, pre-existing chronic disease, and built-up area factors, we found that greater proportions of forest, shrub and scrub, grassland, and herbaceous landscapes were each significantly, negatively correlated with the size of discrepancy in black-white infection rates. The racial disparity in SARS-CoV-2 infection rates was lower in urbanized counties with proportionally more green spaces. The supply of open green space in urban areas and natural green spaces across a county may help to reduce racial disparity in SARS-CoV-2 infection rates through five core mechanisms and one circumstantial mechanism. The findings in this study point to the potential for green spaces to attenuate the racial disparity in health and promote healthy living environments.

Author contributions

B.J. proposed the research concept. Y.L. and B. J. developed the concept into a full research plan. L.C., X.M.L., Y.W.Y., and W.Y.X. conducted the data collection and data analysis under Y.L.'s and B.J.'s supervision. B.J., Y.L., W.C.S., X.M.L., and Y.W.Y. conducted writing of the introduction, discussion, and conclusion. Y.L., L.C., X.M.L., W.Y.X., and Y.W.Y. conducted writing of the methods and results. C.W. provided critical revisions for the introduction and discussion.

Funding

The work done by Dr. Yi Lu in this paper was fully supported by the Research Grants Council of the Hong Kong SAR (GRF Project No. CityU11207520). The work of authors at the University of Hong Kong was supported by the lab funding of the Virtual Reality Lab of Urban Environments and Human Health.

Declaration of Competing 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.

Appendix A

See Tables 1 and 2

Table A1
The definition for socioeconomic and demographic factors, and pre-existing chronic disease factors.

Variable Categories	Variables	Item description (formula)	Official definition	VIF Test
Socioeconomic and demographic factors	Population density	Total population / county area	Population: 2019 county-level census population	Retained
	Female population ratio	Female persons, percent	2019 county-level census female percent	Retained
	Difference in black-white population	Black population / total population - white population / total population	Black: 2019 county-level census black population White: 2019 county-level census white population	Retained
	Difference in black-white older adults	Older adults of black / black population - older adults of white / white population	Older adults: Aged 65 or above.	Retained
	Household size	Persons per household in a county, 2014–2018	Persons per household, or average household size, is obtained by dividing the number of persons in households by the number of households at the county level.	Retained
	Housing value	Median value of owner-occupied housing units, 2014–2018	Specified owner-occupied housing units–one-family houses on less than 10 acres without a business or medical office on the property.	Removed
	Rate of high school graduate or higher	High school graduate or higher, percent of persons age 25 years+, 2014–2018	High school graduates include people whose highest degree was a high school diploma or its equivalent. These data include only persons 25 years old and over.	Removed
	Rate of households with broadband	Households with a broadband Internet subscription, percent, 2014–2018	A Household has a broadband Internet subscription if any household member accesses the Internet.	Retained
	Median household income	Median household income (in 2018 dollars), 2014–2018	Income of households: This includes the income of the householder and all other individuals 15 years old and over in the household, whether they are related to the householder or not.	Retained
	Poverty rate	Persons in poverty, percent (in 2019 census)	Census Bureau uses a set of money income thresholds that vary by family size and composition to determine who is in poverty. If a family's total income is less than the family's threshold, then that family and every individual in it is considered in poverty.	Removed
	Healthcare receipts	Total health care and social assistance receipts/revenue, 2012 ($1,000) / per 100 k	The sector includes both health care and social assistance because it is sometimes difficult to distinguish between the boundaries of these two activities.	Retained
	Travel time to work	Mean travel time to work (minutes), workers age 16 years+, 2014–2018	Travel time to work refers to the total number of minutes that it usually took the person to get from home to work each day during the reference week.	Removed
	Employment rate	Total employment, 2018 / per 100 k	Paid employment consists of full- and part-time employees, including salaried officers and executives of corporations. Included are employees on paid sick leave, holidays, and vacations; not included are proprietors and partners of unincorporated businesses.	Removed
	Number of firms	All firms, 2012 / per 100 k	Firms equally male-/female-owned, equally minority-/nonminority-owned, and equally veteran-/nonveteran-owned are counted and tabulated as separate categories.	Retained
Pre-existing chronic disease factors	Coronary heart disease death rate	Coronary heart disease death rate per 100,000	All ages, all races/ethnicities, both genders, 2016–2018 (not spatial smoothed data)	Retained
	Heart failure death rate	Heart failure death rate per 100,000	All ages, all races/ethnicities, both genders, 2016–2018 (not spatial smoothed data)	Retained
	Diagnosed diabetes rate	Diagnosed diabetes percentage	Age-adjusted percentage, 20+, 2016	Retained
	Obesity rate	Obesity percentage	Age-adjusted percentage, 20 + . 2016	Removed

Note: The detail definition is from the United States Census and Heart disease and stroke data of Centers for Disease Control and Prevention.
Note: All data are at the county level.

Table A2
Official definition of land-cover types: green space and built-up area factors.

Categories	Classes	Official definition	VIF Test
Built-up area factors	Developed Low Intensity	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units.	Removed
	Developed Medium Intensity	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.	Removed
	Developed High Intensity	Highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover.	Removed
Green space factors	Developed open space	Areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.	Retained
	Deciduous forest	Areas dominated by trees generally greater than 5 m tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.	N/A
	Evergreen forest	Areas dominated by trees generally greater than 5 m tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.	N/A
	Mixed forest	Areas dominated by trees generally greater than 5 m tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.	N/A
	Forest	Combination of deciduous, evergreen, and mixed forest.	Retained
	Shrub and scrub	Areas dominated by shrubs; <5 m tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.	Retained
	Grassland and herbaceous	Areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.	Retained
	Pasture and hay	Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.	Retained
	Cultivated crops	Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.	Retained
	Woody wetlands	Areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.	Retained
	Emergent herbaceous wetlands	Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.	Retained

Note: The definition of land classes is derived from The Multi-Resolution Land Characteristics (MRLC) consortium.

References

Abedi, V., Olulana, O., Avula, V., Chaudhary, D., Khan, A., Shahjouei, S., Li, J., Zand, R., 2020. Racial, Economic, and Health Inequality and COVID-19 Infection in the United States. J. Racial Ethnic Health Disparities. https://doi.org/10.1007/s40615-020-00833-4.

Arnberger, A., Eder, R., 2012. The influence of green space on community attachment of urban and suburban residents. Urban For. Urban Greening 11 (1), 41–49. https://doi.org/10.1016/j.ufug.2011.11.003.

Blendon, R.J., Scheck, A.C., Donelan, K., Hill, C.A., Smith, M., Beatrice, D., Altman, D., 1995. How White and African Americans View Their Health and Social Problems: Different Experiences Different Expectations. JAMA 273 (4), 341–346. https://doi.org/10.1001/jama.1995.03520280089048.

Bolund, P., Hunhammar, S., 1999. Ecosystem services in urban areas. Ecol. Econ. 29 (2), 293–301. https://doi.org/10.1016/S0921-8009(99)00013-0.

Branas, C.C., South, E., Kondo, M.C., Hohl, B.C., Bourgois, P., Wiebe, D.J., MacDonald, J. M., 2018. Citywide cluster randomized trial to restore blighted vacant land and its effects on violence, crime, and fear [10.1073/pnas.1718503115]. Proc. Natl. Acad. Sci. http://www.pnas.org/content/early/2018/02/20/1718503115.abstract.

Bratman, G.N., Hamilton, J.P., Daily, G.C., 2012. The impacts of nature experience on human cognitive function and mental health. Ann. N. Y. Acad. Sci. 1249 (1), 118–136. https://doi.org/10.1111/j.1749-6632.2011.06400.x.

Braubach, M., Egorov, A., Mudu, P., Wolf, T., Ward Thompson, C., Martuzzi, M., 2017. Effects of Urban Green Space on Environmental Health, Equity and Resilience. In: Kabisch, N., Korn, H., Stadler, J., Bonn, A. (Eds.), Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice. Springer International Publishing, pp. 187–205. https://doi.org/10.1007/978-3-319-56091-5_11.

Braveman, P.A., Cubbin, C., Egerter, S., Williams, D.R., Pamuk, E., 2010. Socioeconomic Disparities in Health in the United States: What the Patterns Tell Us. Am. J. Public Health 100 (S1), S186–S196. https://doi.org/10.2105/AJPH.2009.166082.

Brooks, A.M., Ottley, K.M., Arbuthnott, K.D., Sevigny, P., 2017. Nature-related mood effects: Season and type of nature contact. J. Environ. Psychol. 54, 91–102. https://doi.org/10.1016/j.jenvp.2017.10.004.

Browning, M.H.E.M., Rigolon, A., 2018. Do Income, Race and Ethnicity, and Sprawl Influence the Greenspace-Human Health Link in City-Level Analyses? Findings from 496 Cities in the United States. Int. J. Environ. Res. Public Health 15 (7). https://doi.org/10.3390/ijerph15071541.

Carlson, S.A., Brooks, J.D., Brown, D.R., Buchner, D.M., 2010. Racial/ethnic differences in perceived access, environmental barriers to use, and use of community parks. Preventing chronic disease, 7(3), Article A49. https://www.scopus.com/inward/record.uri?eid=2-s2.0-77954707975&partnerID=40&md5=ec78e0ddcadd2c1466aa662dd388f28c.

Centers for Disease Control and Prevention. (2020a). Interactive Atlas of Heart Disease and Stroke Tables. https://nccd.cdc.gov/DHDSPAtlas/Reports.aspx.

Centers for Disease Control and Prevention. (2020b). People with Certain Medical Conditions. Retrieved Sep. 26 from https://www.cdc.gov/coronavirus/2019-ncov/need-extra-precautions/people-with-medical-conditions.html.

Chang, D.H.F., Jiang, B., Wong, N.H.L., Wong, J.J., Webster, C., Lee, T.M.C., 2021. The human posterior cingulate and the stress-response benefits of viewing green urban landscapes. NeuroImage 226, 117555. https://doi.org/10.1016/j.neuroimage.2020.117555.

Chiabai, A., Quiroga, S., Martinez-Juarez, P., Suárez, C., García de Jalón, S., Taylor, T., 2020. Exposure to green areas: Modelling health benefits in a context of study heterogeneity. Ecol. Econ. 167, 106401 https://doi.org/10.1016/j.ecolecon.2019.106401.

Cohen, D.A., McKenzie, T.L., Sehgal, A., Williamson, S., Golinelli, D., Lurie, N., 2007. Contribution of Public Parks to Physical Activity. Am. J. Public Health 97 (3), 509–514. https://doi.org/10.2105/AJPH.2005.072447.

Coley, R.L., Sullivan, W.C., Kuo, F.E., 1997. Where Does Community Grow?: The Social Context Created by Nature in Urban Public Housing. Environ. Behav. 29 (4), 468–494. https://doi.org/10.1177/001391659702900402.

Coutts, C., Hahn, M., 2015. Green Infrastructure, Ecosystem Services, and Human Health. Int. J. Environ. Res. Public Health 12 (8), 9768–9798. https://doi.org/10.3390/ijerph120809768.

Doughty, M.R.C., Hammond, G.P., 2004. Sustainability and the built environment at and beyond the city scale. Build. Environ. 39 (10), 1223–1233. https://doi.org/10.1016/j.buildenv.2004.03.008.

Evans, M.K., 2020. Covid's Color Line — Infectious Disease, Inequity, and Racial Justice. N. Engl. J. Med. 383 (5), 408–410. https://doi.org/10.1056/NEJMp2019445.

Figueroa, J.F., Wadhera, R.K., Lee, D., Yeh, R.W., Sommers, B.D., 2020. Community-Level Factors Associated With Racial And Ethnic Disparities In COVID-19 Rates In Massachusetts. Health Aff. 39 (11), 1984–1992. https://doi.org/10.1377/hlthaff.2020.01040.

Fox, J., Weisberg, S., 2018. An R Companion to Applied Regression, 3rd edition. SAGE Publications, Inc. https://socialsciences.mcmaster.ca/jfox/Books/Companion/index.html.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sens. Environ. 202, 18–27. https://doi.org/10.1016/j.rse.2017.06.031.

Hartig, T., Mitchell, R., de Vries, S., Frumkin, H., 2014. Nature and Health. Annu. Rev. Public Health 35 (1), 207–228. https://doi.org/10.1146/annurev-publhealth-032013-182443.

Holtan, M.T., Dieterlen, S.L., Sullivan, W.C., 2014. Social Life Under Cover: Tree Canopy and Social Capital in Baltimore, Maryland. Environ. Behav. 47 (5), 502–525. https://doi.org/10.1177/0013916513518064.

Holtgrave, D.R., Barranco, M.A., Tesoriero, J.M., Blog, D.S., Rosenberg, E.S., 2020. Assessing racial and ethnic disparities using a COVID-19 outcomes continuum for New York State. Ann. Epidemiol. 48, 9–14. https://doi.org/10.1016/j.annepidem.2020.06.010.

Irwin, E.G., Bockstael, N.E., 2007. The evolution of urban sprawl: Evidence of spatial heterogeneity and increasing land fragmentation. Proc. Natl. Acad. Sci. 104 (52), 20672. https://doi.org/10.1073/pnas.0705527105.

Jiang, B., Chang, C.-Y., Sullivan, W.C., 2014. A dose of nature: Tree cover, stress reduction, and gender differences. Landscape Urban Plann. 132, 26–36. https://doi.org/10.1016/j.landurbplan.2014.08.005.

Jiang, B., He, J., Chen, J., Larsen, L., 2021. Moderate is optimal: A simulated driving experiment reveals freeway landscape matters for driving performance. Urban For. Urban Greening 126976.

Jiang, B., He, J., Chen, J., Larsen, L., Wang, H., 2020. Perceived Green at Speed: A Simulated Driving Experiment Raises New Questions for Attention Restoration Theory and Stress Reduction Theory. Environ. Behav. 0013916520947111 https://doi.org/10.1177/0013916520947111.

Jiang, B., Schmillen, R., Sullivan, W.C., 2018. How to Waste a Break: Using Portable Electronic Devices Substantially Counteracts Attention Enhancement Effects of Green Spaces. Environ. Behav. 51 (9–10), 1133–1160. https://doi.org/10.1177/0013916518788603.

Jiang, B., Zhang, T., Sullivan, W.C., 2015. Healthy Cities: Mechanisms and Research Questions Regarding the Impacts of Urban Green Landscapes on Public Health and Well-being. Landsc. Archit. Front. 3 (1), 24–35. https://doi.org/10.1007/slaf-0024-0301-xx.

Kaplan, S., 1995. The restorative benefits of nature: Toward an integrative framework. J. Environ. Psychol. 15 (3), 169–182. https://doi.org/10.1016/0272-4944(95)90001-2.

Kawachi, I., Daniels, N., Robinson, D.E., 2005. Health Disparities By Race And Class: Why Both Matter. Health Aff. 24 (2), 343–352. https://doi.org/10.1377/hlthaff.24.2.343.

Khunti, K., Singh, A.K., Pareek, M., Hanif, W., 2020. Is ethnicity linked to incidence or outcomes of covid-19? BMJ 369, m1548. https://doi.org/10.1136/bmj.m1548.

Klompas, M., Baker, M.A., Rhee, C., 2020. Airborne Transmission of SARS-CoV-2: Theoretical Considerations and Available Evidence. JAMA 324 (5), 441–442. https://doi.org/10.1001/jama.2020.12458.

Kuo, F.E., Bacaicoa, M., Sullivan, W.C., 1998. Transforming Inner-City Landscapes: Trees, Sense of Safety, and Preference. Environment and behavior 30 (1), 28–59. https://doi.org/10.1177/0013916598301002.

Kuo, F.E., Sullivan, W.C., 2001a. Aggression and violence in the inner city - Effects of environment via mental fatigue. Environ. Behav. 33 (4), 543–571. <Go to ISI>://000173727900004.

Kuo, F.E., Sullivan, W.C., 2001b. Aggression and Violence in the Inner City: Effects of Environment via Mental Fatigue. Environ. Behav. 33 (4), 543–571. https://doi.org/10.1177/00139160121973124.

Kuo, F.E., Taylor, A.F., 2004. A Potential Natural Treatment for Attention-Deficit/Hyperactivity Disorder: Evidence From a National Study. Am. J. Public Health 94 (9), 1580–1586. http://search.ebscohost.com/login.aspx?direct=true&db=rss&AN=14277091&site=ehost-live.

Leclerc, Q., Fuller, N., Knight, L., null, n., Funk, S., & Knight, G., 2020. What settings have been linked to SARS-CoV-2 transmission clusters? Wellcome Open Res., 5, 83. https://doi.org/10.12688/wellcomeopenres.15889.2.

Lovasi, G.S., Hutson, M.A., Guerra, M., Neckerman, K.M., 2009. Built Environments and Obesity in Disadvantaged Populations. Epidemiol. Rev. 31 (1), 7–20. https://doi.org/10.1093/epirev/mxp005.

Lu, Y., 2019. Using Google Street View to investigate the association between street greenery and physical activity. Landscape Urban Plann. 191, 103435 https://doi.org/10.1016/j.landurbplan.2018.08.029.

Lu, Y., Sarkar, C., Xiao, Y., 2018. The effect of street-level greenery on walking behavior: Evidence from Hong Kong. Soc. Sci. Med. 208, 41–49. https://doi.org/10.1016/j.socscimed.2018.05.022.

Markevych, I., Schoierer, J., Hartig, T., Chudnovsky, A., Hystad, P., Dzhambov, A.M., de Vries, S., Triguero-Mas, M., Brauer, M., Nieuwenhuijsen, M.J., Lupp, G., Richardson, E.A., Astell-Burt, T., Dimitrova, D., Feng, X., Sadeh, M., Standl, M., Heinrich, J., Fuertes, E., 2017. Exploring pathways linking greenspace to health: Theoretical and methodological guidance. Environ. Res. 158, 301–317. https://doi.org/10.1016/j.envres.2017.06.028.

Massey, D.S., 2001. Residential segregation and neighborhood conditions in US metropolitan areas. Am. Becoming: Racial Trends Their Consequences 1 (1), 391–434.

Mitchell, R., Popham, F., 2008. Effect of exposure to natural environment on health inequalities: an observational population study. The Lancet 372 (9650), 1655–1660. https://doi.org/10.1016/S0140-6736(08)61689-X.

Mody, A., Pfeifauf, K., Bradley, C., Fox, B., Hlatshwayo, M.G., Ross, W., Sanders-Thompson, V., Joynt, K., Reidhead, M., Schootman, M., Powderly, W.G., Geng, E.H., 2020. Understanding Drivers of COVID-19 Racial Disparities: A Population-Level Analysis of COVID-19 Testing among Black and White Populations. Clin. Infect. Dis. https://doi.org/10.1093/cid/ciaa1848.

Nowak, D.J., Hirabayashi, S., Bodine, A., Greenfield, E., 2014. Tree and forest effects on air quality and human health in the United States. Environ. Pollut. 193, 119–129. https://doi.org/10.1016/j.envpol.2014.05.028.

O'brien, R.M., 2007. A Caution Regarding Rules of Thumb for Variance Inflation Factors. Qual. Quant., 41, 5, 673–690. https://doi.org/10.1007/s11135-006-9018-6.

Payne-Sturges, D., Gee, G.C., 2006. National environmental health measures for minority and low-income populations: Tracking social disparities in environmental health. Environ. Res. 102 (2), 154–171. https://doi.org/10.1016/j.envres.2006.05.014.

Phelan, J.C., Link, B.G., 2015. Is Racism a Fundamental Cause of Inequalities in Health? Ann. Rev. Sociol. 41 (1), 311–330. https://doi.org/10.1146/annurev-soc-073014-112305.

Popescu, I., Duffy, E., Mendelsohn, J., Escarce, J.J., 2018. Racial residential segregation, socioeconomic disparities, and the White-Black survival gap. PLoS ONE 13 (2), e0193222. https://doi.org/10.1371/journal.pone.0193222.

Pretty, J., Peacock, J., Sellens, M., Griffin, M., 2005. The mental and physical health outcomes of green exercise. Int. J. Environ. Health Res. 15 (5), 319–337. https://doi.org/10.1080/09603120500155963.

R Core Team. (2020). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Available: http://www.R-project.org [accessed 1 Oct 2020].

Richardson, E.A., Mitchell, R., Hartig, T., de Vries, S., Astell-Burt, T., Frumkin, H., 2012. Green cities and health: a question of scale? J. Epidemiol. Community Health 66 (2), 160. https://doi.org/10.1136/jech.2011.137240.

Rigolon, A., 2016. A complex landscape of inequity in access to urban parks: A literature review. Landscape Urban Plann. 153, 160–169. https://doi.org/10.1016/j.landurbplan.2016.05.017.

Rook, G.A., 2013. Regulation of the immune system by biodiversity from the natural environment: An ecosystem service essential to health. Proc. Natl. Acad. Sci. 110 (46), 18360. https://doi.org/10.1073/pnas.1313731110.

Rozenfeld, Y., Beam, J., Maier, H., Haggerson, W., Boudreau, K., Carlson, J., Medows, R., 2020. A model of disparities: risk factors associated with COVID-19 infection. Int. J. Equity Health 19 (1), 126. https://doi.org/10.1186/s12939-020-01242-z.

Shi, Y., Wang, Y., Shao, C., Huang, J., Gan, J., Huang, X., Bucci, E., Piacentini, M., Ippolito, G., Melino, G., 2020. COVID-19 infection: the perspectives on immune responses. Cell Death Differ. 27 (5), 1451–1454. https://doi.org/10.1038/s41418-020-0530-3.

Singh, G.K., Yu, S.M., 2019. Infant Mortality in the United States, 1915–2017: Large Social Inequalities have Persisted for Over a Century. Int. J. MCH and AIDS 8 (1), 19–31. https://doi.org/10.21106/ijma.271.

Sullivan, W.C., Kuo, F.E., Depooter, S.F., 2004. The Fruit of Urban Nature: Vital Neighborhood Spaces. Environ. Behav. 36 (5), 678–700. https://doi.org/10.1177/0193841X04264945.

Suppakittpaisarn, P., Jiang, B., Slavenas, M., Sullivan, W.C., 2019. Does density of green infrastructure predict preference? Urban For. Urban Greening 40, 236–244. https://doi.org/10.1016/j.ufug.2018.02.007.

Suppakittpaisarn, P., Jiang, X., Sullivan, W.C., 2017. Green Infrastructure, Green Stormwater Infrastructure, and Human Health: A Review. Curr. Landscape Ecol. Reports 2 (4), 96–110. https://doi.org/10.1007/s40823-017-0028-y.

Tai, D.B.G., Shah, A., Doubeni, C.A., Sia, I.G., Wieland, M.L., 2020. The Disproportionate Impact of COVID-19 on Racial and Ethnic Minorities in the United States. Clin. Infect. Dis. https://doi.org/10.1093/cid/ciaa815.

Taylor, A.F., Kuo, F.E., Sullivan, W.C., 2002a. Views of nature and self-discipline: Evidence from inner city children. J. Environ. Psychol. 22 (1), 49–63. https://doi.org/10.1006/jevp.2001.0241.

Taylor, A.F., Kuo, F.E., Sullivan, W.C., 2002b. Views of nature and self-discipline: Evidence from inner city children. J. Environ. Psychol. 22 (1–2), 49–63. http://www.scopus.com/inward/record.url?eid=2-s2.0-0036292402&partnerID=40&md5=cfcff438f2e4212f7b2afee68356c91b.

Townsend, M.J., Kyle, T.K., Stanford, F.C., 2020. Outcomes of COVID-19: Disparities in obesity and by ethnicity/race. Int. J. Obes. 44 (9), 1807–1809. https://doi.org/10.1038/s41366-020-0635-2.

Ulrich, R.S., Simons, R.F., Losito, B.D., Fiorito, E., Miles, M.A., Zelson, M., 1991. Stress recovery during exposure to natural and urban environments. J. Environ. Psychol. 11 (3), 201–230. http://www.sciencedirect.com/science/article/B6WJ8-4GK8NPT-1/2/aca5972eb250c78fd991457187117cc2.

United States Census Bureau. (2019). U.S. Census Bureau Releases 2014-2018 ACS 5-Year Estimates. Available: https://www.census.gov/programs-surveys/acs/news/updates/2019.html [accessed 1 Oct 2020].

United States Census Bureau. (2020). Annual County Resident Population Estimates by Age, Sex, Race, and Hispanic Origin: April 1, 2010 to July 1, 2019 (CC-EST2019-ALLDATA). Available: from https://www.census.gov/data/tables/time-series/demo/popest/2010s-counties-detail.html [accessed 26 Sep 2020].

Webb Hooper, M., Nápoles, A.M., Pérez-Stable, E.J., 2020. COVID-19 and Racial/Ethnic Disparities. JAMA 323 (24), 2466–2467. https://doi.org/10.1001/jama.2020.8598.

Webster, C., 2010. Pricing accessibility: Urban morphology, design and missing markets. Progr. Plann. 73 (2), 77–111. https://doi.org/10.1016/j.progress.2010.01.001.

Wen, M., Zhang, X., Harris, C.D., Holt, J.B., & Croft, J.B., 2013. Spatial disparities in the distribution of parks and green spaces in the USA. Annals of behavioral medicine : a publication of the Society of Behavioral Medicine, 45 Suppl 1(Suppl 1), S18-S27. https://doi.org/10.1007/s12160-012-9426-x.

Williams, D.R., Priest, N., Anderson, N.B., 2016. Understanding associations among race, socioeconomic status, and health: Patterns and prospects. Health Psychol.: Official J. Divis. Health Psychol., Am. Psycholog. Assoc. 35 (4), 407–411. https://doi.org/10.1037/hea0000242.

Williams, D.R., Sternthal, M., 2010. Understanding Racial-ethnic Disparities in Health: Sociological Contributions. J. Health Soc. Behav. 51 (1_suppl), S15–S27. https://doi.org/10.1177/0022146510383838.

Wolch, J.R., Byrne, J., Newell, J.P., 2014. Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. Landscape Urban Plann. 125, 234–244. https://doi.org/10.1016/j.landurbplan.2014.01.017.

Wrigley-Field, E., 2020. US racial inequality may be as deadly as COVID-19. Proc. Natl. Acad. Sci. 117 (36), 21854. https://doi.org/10.1073/pnas.2014750117.

Wu, S.L., Mertens, A.N., Crider, Y.S., Nguyen, A., Pokpongkiat, N.N., Djajadi, S., Seth, A., Hsiang, M.S., Colford, J.M., Reingold, A., Arnold, B.F., Hubbard, A., Benjamin-

Chung, J., 2020. Substantial underestimation of SARS-CoV-2 infection in the United States. Nat. Commun. 11 (1), 4507. https://doi.org/10.1038/s41467-020-18272-4.
Yancy, C.W., 2020. COVID-19 and African Americans. JAMA, 323, 19, 1891–1892. https://doi.org/10.1001/jama.2020.6548.
Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S.M., Case, A., Costello, C., Dewitz, J., Fry, J., Funk, M., Granneman, B., Liknes, G.C., Rigge, M., Xian, G., 2018. A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. ISPRS J. Photogramm. Remote Sens. 146, 108–123. https://doi.org/10.1016/j.isprsjprs.2018.09.006.
Yu, K., Li, D., Li, N., 2006. The evolution of Greenways in China. Landscape Urban Plann. 76 (1–4), 223–239. https://doi.org/10.1016/j.landurbplan.2004.09.034.
Zhang, R., Li, Y., Zhang, A.L., Wang, Y., Molina, M.J., 2020. Identifying airborne transmission as the dominant route for the spread of COVID-19. Proc. Natl. Acad. Sci. 117 (26), 14857. https://doi.org/10.1073/pnas.2009637117.
Zhu, Y., Xie, J., Huang, F., Cao, L., 2020. Association between short-term exposure to air pollution and COVID-19 infection: Evidence from China. Sci. Total Environ. 727, 138704 https://doi.org/10.1016/j.scitotenv.2020.138704.