Using GIS-based spatial analysis to determine urban greenspace accessibility for different racial groups in the backdrop of COVID-19: a case study of four US cities

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Abstract As the United States leads COVID-19 cases on global charts, its spatial distribution pattern offers a unique opportunity for studying the social and ecological factors that contribute to the pandemic's scale and size. We use a GIS-data-based approach to evaluate four American cities—Anchorage (Alaska), Atlanta (Georgia), Phoenix (Arizona), and Portland (Oregon) characterized by the significant composition of different racial and ethnic group populations. Building upon previous studies that investigated urban spatial inequalities using the environmental justice framework, we examine: (1) the relative racial vulnerability of Census Block Groups (CBG) and ZIP Code Tabulation Areas (ZCTA) to COVID-19 (2) green space distribution at CBG and ZCTA scale. Using standard normalization methods, we ranked racial vulnerability against % available green space for each city. Our results highlight the legacy of past and present urban planning injustices. The project is useful from environmental justice, public health management, and urban planning perspectives.

Keywords Urban inequality · Racial vulnerability · Environmental justice · Green space · COVID-19

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Introduction

The first case of COVID-19 in the United States (U.S.) was reported on Jan 20, 2020, in Snohomish County, WA, and the disease spread with varying intensities of outbreak from state to state. Some states reached their peak early while the virus took longer to spread in others. The pandemic has impacted all 50 states and over 33 million confirmed cases have been reported as of June 15, 2021, by the WHO. With a vast number of cases being reported in population centers such as California, Florida, Texas, and New York (Oster et al., 2020), the cases have increased at an alarming rate since the initial spread in mid-March of 2020. The U.S government took some necessary steps to stop the spread of infectious disease with travel restrictions

across the country (Executive Order No. 13909, 2020). During the period, the COVID-19 response was highly decentralized, and the states were subjected to varying levels of enforcement as per the directives issued by state and local officials. Travel restrictions, stay-at-home orders, social distancing, and mask-mandates were some of the guidelines that were suggested to control the spread of the disease. The U.S. performed a high number of COVID-19 tests but suffered setbacks due to faulty diagnostic kits initially, and the early spread of the disease went undetected for weeks. As of June 15, 2021, 480 million tests have been conducted in the country. Over 597 thousand deaths due to COVID-19 have been reported across the U.S. (Centers for Disease Control and Prevention 2021).

The geographic areas and hotspots in the U.S. which have been most affected by COVID-19 have changed over time, and various social and ecological factors have played an important role in controlling the spread of this pandemic (Desjardins et al., 2020; Hohl et al., 2020). This changing spatial pattern can be evaluated by identifying hotspots and green zones at different stages of the pandemic and comparing the pattern of socio-ecological factors in the various cities. Previous studies have found that the spatial scope of an infectious disease can be controlled by several factors associated with the transmission such as epidemiological, demographic, social, and ecological (Gostin, 2019; Kubota et al., 2020; Sobral et al., 2020; Tamerius et al., 2013). According to Houeto (2019), a complex suite of sociological and economic factors such as education, occupation, and income influence human movement across the landscape and can have critical impacts on outbreak dynamics and the spatial spread of infectious disease.

It is also known that many pronounced changes in human social ecology have rapidly altered the spread of infectious diseases such as population size and density; urbanization; political ignorance; differences in built environment; science and technology; and poor health awareness (Weiss & McMichael, 2004). Among the social factors, population density has been identified as a crucial entity for the transmission of the pandemic. Oster et al. (2020) has identified that counties with small population sizes are less likely to be considered a hotspot and the cases are monitored with the primary focus on the trends in the counties nearby. Also, due to the limited interaction between people in cities with lesser population size delays the impact and slows down the process of transmission.

The green spaces of a city, such as parks, have a positive impact on the health of its inhabitants (Cicea & Pirlogea, 2011). Cities with insufficient green space for their residents suffer from an overflow of people in a few available parks, which makes it difficult to follow social distancing. Studies also show that green spaces improve the quality of life during pandemic outbreaks (Kleinschroth & Kowarik, 2020; Xie et al., 2020). Additionally, outdoor spaces such as parks and trails are considered relatively safer due to constant air circulation (Mayo Clinic, 2020, Olin, 2020). Similarly, lakes, beaches, and wetlands are considered safer for recreation, with appropriate social distancing in place (Centers for Disease Control and Prevention, 2020a). Liu et al. (2019), however, argue that an increase in the green space of a city will not directly lead to healthier living conditions because not all residents have equal access to green spaces.

In a study about spatial disparities in the distribution of parks and green spaces, Nesbitt et al. (2018) suggest that disadvantaged neighborhoods like those inhabited by poor, Black, or Hispanic populations are underexposed to green spaces. Shorter living distance to the park does provide spatial access but factors such as safety, traffic, and walkability affect the park utilization as well. Nesbitt et al. (2018) conclude that the access to urban vegetation is lesser for racialized minorities but less common according to multivariate analyses. They also opine that variables like education, income, and population density should be taken into account during this investigation.

Ethnic and racial disparities correspond heavily to the inequalities in social determinants and seem to increase the risk of COVID-19 (Centers for Disease Control and Prevention 2020b). Although African American and LatinX communities constituted only 13% and 18% of the US population in 2020 respectively, 22% of COVID-19 deaths were African Americans and 38% were Latinx. American Indian and Alaska Natives make up 2.1% of the entire US population, however, COVID-19 mortality rates were 2.4 times higher than that of White Americans during the first wave (Centers for Disease Control and Prevention, 2020a, b). Similarly, Ramírez and Lee (2020) concluded that the rate of death due to COVID is relatively higher in rural counties due to lack of access to health care, poverty, and unhygienic living

conditions. They also suggest that the number of cases is alarmingly high in people of Hispanic, Non-Hispanic Black, and non-Hispanic Native Hawaiian or Pacific Islander origins considering the fact that they only make up 25.6% of Colorado's population. Karaca-Mandic et al. (2021) analyzed COVID-19 hospitalization data in 12 states between April and June 2020, concluding that the percentage of hospitalizations among white patients was much lower compared to their representative share in the State population in all 12 states, while the percentage of hospitalizations among Black patients were much higher. The impact of COVID-19 is visibly higher in such communities of color compared to white Americans and Asian Americans. Further research is required in this part to assess the impact of the COVID-19 outbreak on various races and communities. The association between green space and infectious disease has not yet been explored completely.

While racial disparity of green space accessibility has been widely studied at the census tract level (Dai, 2011; Lanza et al., 2019; Liu et al., 2021; Wen et al., 2013), studies at the census block group (CBG) level are lacking, except a study by So (2016). CBG is the smallest geographic census unit and is a subset of census tract; census tracts have populations ranging from 1200 to 8000, compared to CBGs which range from 600 to 3000 people. Additionally, many ecological variables are available at a much finer scale than a census tract. Therefore, using census tract might mask the spatial heterogeneity of ecological variables. Therefore, using block groups offers a much finer geographic resolution to better understand spatial disparities in sociodemographic and ecological variables. Nonetheless, many studies rely on census tracts since all data are not generally accessible at the CBG scale, and some other researchers who employ qualitative data avoid the best resolution for ethical concerns. Thus, there exists a significant gap in that these social and ecological factors have not been thoroughly studied as a unit at CBG scale. The compilation of such data could help in estimating disease spread at multiple scales (Table 1). Lu et al. (2021) showed that the disparity is significantly smaller in areas with a higher ratio of green spaces at the county level, and Andersen et al. (2021) revealed that race is one of the factors associated with community-level COVID vulnerability. CDC data reveals that there is a great deal of disparity in COVID-

19 vulnerability among different races and ethnicities. Racial vulnerability (RV) is, therefore, the response pattern of different races and ethnicities to COVID-19, based on infection and mortality rate in the US. We define RV as each racial group's relative vulnerability to COVID-19 based on national-scale disparities in COVID-19 infection and mortality rates (Louis-Jean et al., 2020; Muñoz-Price et al., 2020; Zelner et al., 2020).

COVID-19 data is typically available for limited geographies at a resolution of ZIP Code Tabulation Areas (ZCTA), a geographical unit for which the US census bureau publishes data. Thus, we also related RV and green space to COVID-19 numbers at ZCTA for available geographies.

Since COVID-19 cases are found in cities of different sizes, we see a need for a standardized mechanism to identify how RV at the CBG contributes to the spread of COVID-19 and how governments can ensure equity in green space access. Thus, we base our research on the following questions:

1. What are the spatial patterns of RV to COVID-19 in cities?
2. How does green space distribution relate to RV at the CBG and ZCTA scales?

Environmental justice framework

Environmental injustice greatly impacts communities of color and low-income communities. People might live in the same area but their race, ethnicity, wealth, or income might cause them to experience widely varying qualities of air, water, and life. The pandemic has shone a light on social and environmental injustices in terms of healthcare, housing, and urban green spaces (Bashir et al., 2020; Haase, 2020; Prowers et al., 2021). Environmental justice seeks to reduce health disparities while identifying and addressing the social inequalities involved. The environmental justice framework is an important tool where the health inequities and public health outcomes are evaluated by assessing the environmental exposure, biological, and socioeconomic factors. It sheds light on the community democratic decision-making processes and political forces and involves residents and local organizations, researchers, advocates, and policymakers (Kreger et al., 2011). The objective is to provide

Table 1 Brief literature review on empirical studies investigating the relationship between COVID-19 and urban environment

Authors	Study area	Focus	Summary
Andersen et al. (2021)	All counties and county-equivalents in the USA	Geographic hotspots and community drivers associated with spatial patterns of COVID-19 transmission	The factors associated with community-level vulnerability included age, disability, language, race, occupation, and urban status
Dong et al. (2020)	Wuhan, China	Connectivity and public green space (PGS) use	There is no high correlation between PGS use and its connectivity
Louis-Jean et al. (2020)	Selected counties or county-equivalents, and cities in the USA	Racial Disparities	This communication provides a brief overview of the health inequalities resulting in African Americans dying disproportionately during the COVID-19 pandemic
McPhearson et al. (2020)	New York City, USA	Spatial and Social Distributions of the first wave of COVID-19 and social vulnerability indicators	Social Vulnerability indicators (e.g., race, language, income, etc.) drive spatial patterns in the prevalence of COVID-19 testing, confirmed cases, death rates, and severity
Pan et al. (2021)	All urban boroughs of London	Public green space (PGS) accessibility and high choice measures	The results indicate higher transmission possibility without characterizing the infrastructure and social conditions
Tribby and Hartmann (2021)	New York City, USA	Built environment characteristics and COVID-19 cases	Positive associations between COVID-19 cases and % black, Hispanic population, % population over 65
Lu et al. (2021)	135 most urbanized counties across the United States	Relationship between green spaces and racial disparity to COVID-19 at the county level	The disparity is significantly smaller in areas with a higher ratio of green spaces at the county level
Zelner et al. (2020)	Michigan, USA	Racial Disparities	Presents racial disparity trends

and maintain a healthy and sustainable environment for everyone without the intersections of race, class, gender, ability, age, and climate. The framework of environmental justice extends beyond air pollution and also includes the provision of green spaces, water quality, protection from environmental events, and noise pollution (Pearce, 2013). The studies consistently point out that the communities of color and low-income or otherwise vulnerable individuals are at greater risk of exposure, and they have fewer resources to respond to the health issues posed by the environmental factors (Norris & Gonzalez, 2020; Watson et al., 2020).

Urban areas are active environmental systems having mutually dependent ecological, physical, and social components. The structure and diversity of urban landscapes often demonstrate stratification of wealth and power in the community (Schell et al., 2020; Watson et al., 2020). The constant processes of suburbanization have contributed immensely to the contemporary patterns of environmental racism.

Environmental racism not only refers to people of color and low-income groups getting disproportionately exposed to pollution but also involves biases in natural resource policy and uneven enforcement of environmental regulations (Pulido, 2016). Some geographic studies of environmental racism have discussed the spatial relationships between environmental hazards and the demographic data to evaluate the presence of inequity (Brulle & Pellow, 2006; Mohai et al., 2009). In our research we consider this case of environmental injustice to examine the access to green spaces for different racial groups and examine the disproportionate impact it has on the health of the vulnerable population in the context of the COVID-19 pandemic.

One of the most notable observations in 2020 about documented COVID-19 infections and deaths has been the significant impact the pandemic has had on people of color. According to data from the American Public Media Research Lab, Asian Americans have faced a mortality rate of one in 1040 individuals,

compared to one in every 390 for Indigenous Americans. White Americans have recorded one fatality for every 665 individuals, whereas Blacks have recorded one for every 555 individuals (APM, 2021). A possible explanation for this disparity is that whites and Asians are comparatively healthier, wealthier, and better educated than other racial and ethnic groups, though internal disparities do exist within white and Asian communities (Centers for Disease Control and Prevention, 2016

In theory, everyone can get COVID; however, we believe there is a need to assess relative RV to COVID-19 at the census block group level to properly share resources among all population groups to build community resilience against future pandemics. Urban green spaces are an example of resources that provide several ecosystem benefits, especially during times of social and economic crises (Grima et al., 2020). More green and open places allow people to engage in physical and mental recreation during pandemics such as COVID-19. The RV concept we propose stems from historical urban planning policies, and it can only be addressed by an equitable and collaborative distribution of resources. Thus, we propose the following framework (Fig. 1), in which high RV to COVID-19 is aggravated by a scarcity of green spaces, while low RV to COVID-19 is aided by an abundance of green spaces.

Study area

Our study area includes Anchorage (AK), Portland (OR), Phoenix (AZ), and Atlanta (GA), USA.

These four cities were chosen because they vary in size, population, population density, and climate characteristics (Table 2). These cities also displayed an increasing pattern of COVID-19 infection and mortality rates in 2020 (Fig. 2). We intentionally avoided cities with very high population densities (e.g., New York, San Francisco) because our findings might be skewed. Instead, we seek to investigate cities of wide variations to identify whether we could find comparable or different trends.

Anchorage has the smallest population, but it has one of the highest per capita green space distributions in the country, with a total of 4429 hectares of park and open spaces (Municipality of Anchorage (MUNI), 2018; Pallathadka et al., 2021). Anchorage is also a very diverse city, ranking in the 80th percentile of American cities for ethnic diversity (Farrell, 2018). In addition to having a large number of Alaska Natives, Anchorage saw a remarkable increase in racial diversity since 1980. It has become a magnet for Asian, Pacific Island, Latino, and multiracial populations. While many neighborhoods in Anchorage are relatively homogeneous in terms of race and ethnicity, several are incredibly diverse. According to Chad Farrell (2018), Anchorage possesses the three most diverse census tracts in the entire United States as well as more than half a dozen census tracts that rank quite high in terms of diversity. These tracts are not concentrated in just one part of the city but are distributed across the broad areas of the city identified as "downtown" and "midtown", near many of the parks previously mentioned. Similarly, Anchorage's schools are exceptionally diverse with 19 of the 20 most diverse elementary schools in the United States being found in the municipality (Farrell, 2018). Portland is a fascinating test case due to its largely white population. A look back at Portland's and Oregon's history reveals a discriminatory past in which non-whites were not legally allowed to buy land or become permanent inhabitants. Even after the legislation was repealed in 1926, segregation and other government measures hindered minorities from ever completely settling in Portland's neighborhoods. Although recent decades have shown promise with modest gains in non-white population, Portland, as one of America's largest white cities, proves to be a useful study city for analyzing trends in urban policy and how they impact local inhabitants. Furthermore, Forest Park in northwest Portland is one of the largest urban parks in the country (City of Portland, 2021).

Phoenix has the largest population among our study cities. Phoenix is also one of the fastest-growing cities in the United States, with a sizable Hispanic community. Phoenix was previously a part of Northern Mexico until the United States annexed the northern zone of Mexico during the Mexican–American War in 1848. Phoenix was founded 20 years later. Prior to the twentieth century, more than half of the population was Mexican citizens and Mexican-Americans, and they had very friendly ties with the non-Hispanic community—but that began to change as more people moved westward in the twentieth century. Despite problems of housing segregation in the early twentieth century and politics around immigration and crime
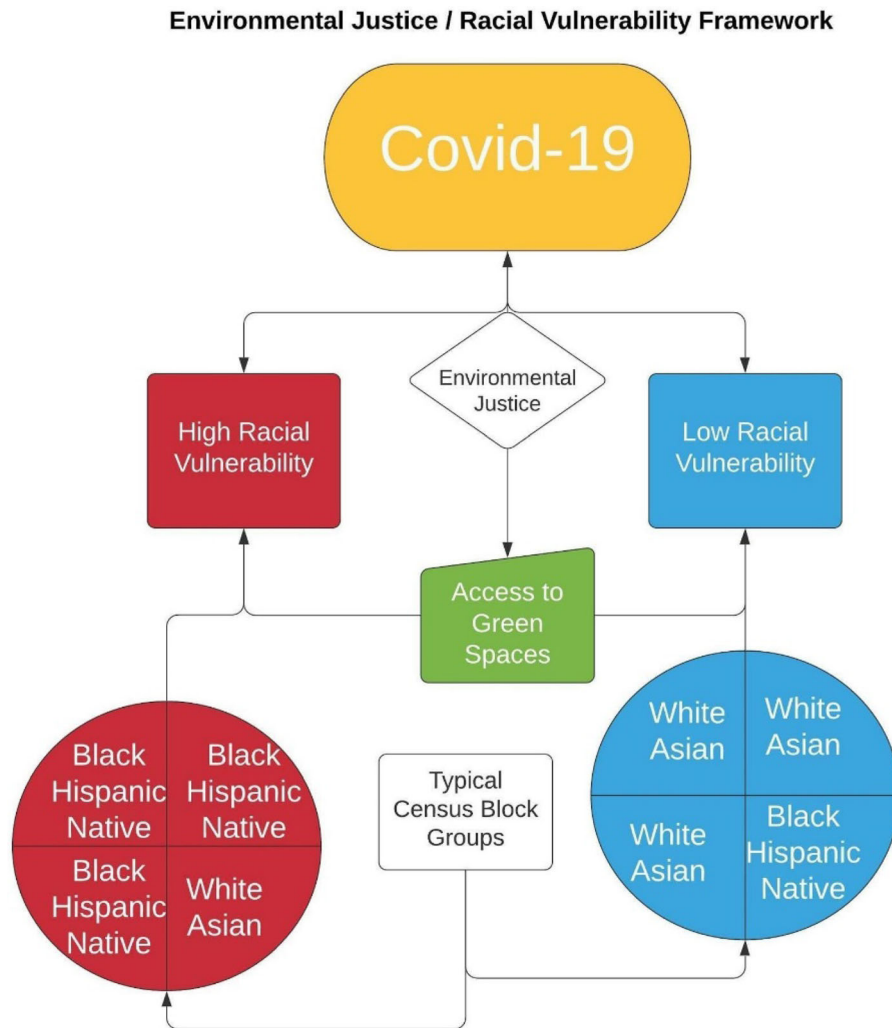
Environmental Justice / Racial Vulnerability Framework

Fig. 1 Environmental Justice/RV Framework for understanding spatial variation of COVID-19

from the 1990s onwards, Phoenix has maintained a remarkable diversity in its population in recent years. With its distinctive arid environment, Phoenix has been expanding parks and green spaces to address a variety of issues, including urban heat islands (City of Phoenix, 2010).

Atlanta displays the highest population density among our study cities. It is also distinctive in that the majority of the population is black. Jim Crow laws caused social segregation in Atlanta in the early twentieth century, thus it was only natural that Atlanta would also serve as a major civil rights hub in the 1960s. In the 1970s, African Americans were the majority in Atlanta for the first time. As African Americans suburbanized in the 2000s, racial

transformation has been ongoing. Despite existing social challenges, Atlanta is expanding its park and trail network as part of the Atlanta Beltline plan, which is anticipated to be completed by 2030 (City of Atlanta, 2021).

Data and methods

Data

Demographic data

Population and Demographic data for 2018 was obtained from the American Community Survey

Table 2 Main physical and sociodemographic characteristics of study cities

| City	Anchorage	Portland	Atlanta	Phoenix
Climate classification (Köppen)	Subarctic (Dsc)	Warm summer Mediterranean (Csb)	Humid subtropical (Cfa)	Hot desert (BWh)
Population	291,538	653,115	498,044	1,680,992
Population density (Km^2)	58	1739	5188	1255
Precipitation (mm)	422.5	914.5	1262.5	204
Park acreage (2018)	10,946	12,591	3867	43,609
Park acres as % of land area	39.90	15.70	4.60	14.30
Total COVID-19 deaths (as of June 1, 2021)	174	500 ~	1500 ~	7500 ~
Total COVID-19 cases (as of June 1, 2021)	30,556	31,808	150,000 ~	275,000 ~
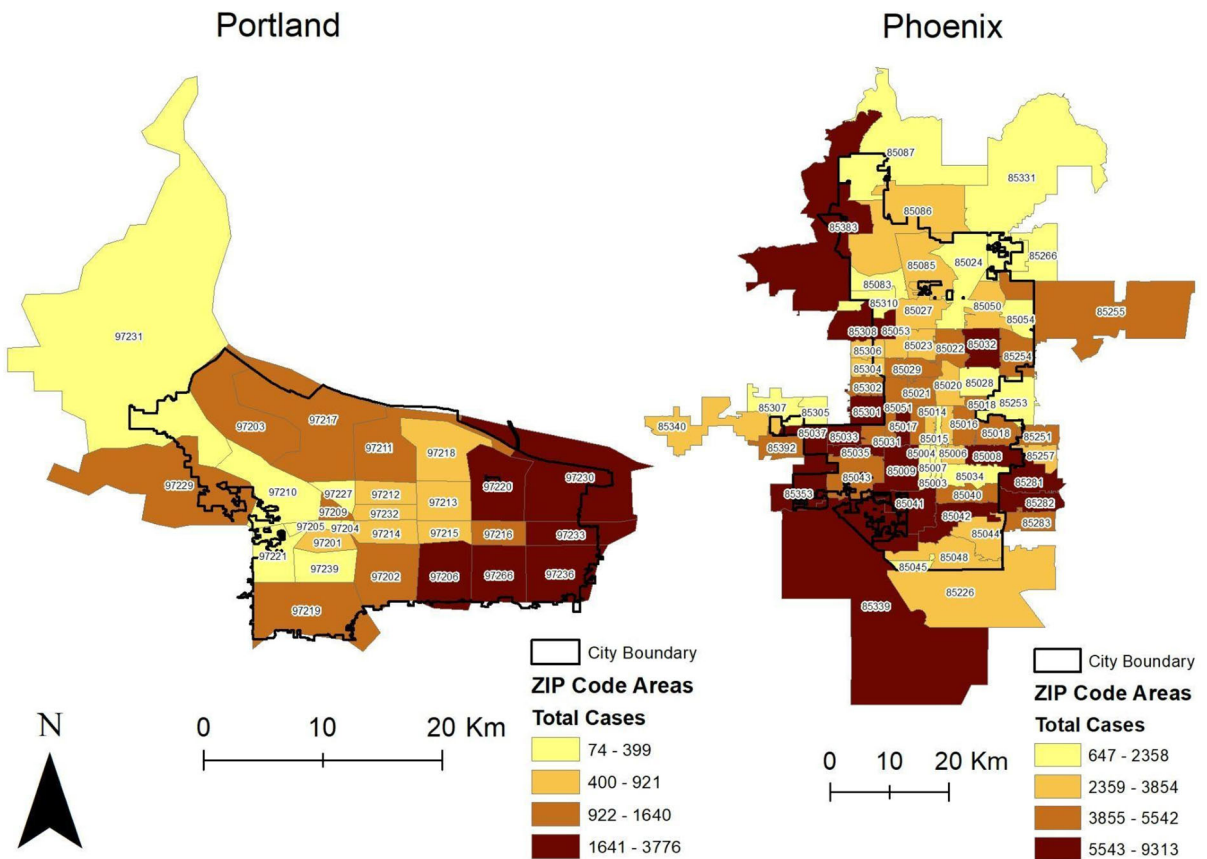
Fig. 2 Map showing total COVID-19 cases by ZIP code in study cities as of June 15, 2021. Anchorage and Atlanta's data were unavailable/incomplete

(ACS) platform's 2018 5-year estimates (U.S. Census Bureau, 2020). The ACS platform provides nationwide population estimates at different scales, census block groups (CBGs) being the smallest unit. We obtained TIGER line shapefiles and CBGs from the US Census Bureau. We created COVID-19 case data

at the ZIP code level by merging the ZIP Code Tabulation Areas (ZCTA) shapefile with publicly available statistics of COVID-19 cases by ZIP code.

Green space layers data

We created the green space layer by combining three different datasets (Table 3). The first dataset i.e., parks and trails layer was obtained from each city's GIS department, the second dataset i.e., beaches (where applicable) was sourced from State GIS departments, and the third dataset i.e., Wetlands was accessed from the National Wetlands Inventory (U.S. Fish and Wildlife Service, 2020).

Methods

Spatial analysis

We performed spatial analysis (Fig. 3) on ArcGIS Desktop using *spatial analyst* tools (ArcMap 10.8.1). First, we imported the census and green space datasets into ArcMap and intersected each dataset with the polygons of the respective city. Following that, we summarized both datasets for each CBG. Then, for each racial group with a positive (+) relationship with COVID-19 (e.g., Native, Table 4), we normalized their values using a linear standardization formula to rescale values between 0 and 1 (Eq. 1) (Chang et al., 2021).

$$V_i = \frac{X_i - X_{imin}}{X_{imax} - X_{imin}} \quad (1)$$

i is the variable being analyzed, in this case either racial group or green space. j is the city in which the analysis is being done: Anchorage, AK; Atlanta, GA; Phoenix, AZ; or Portland, OR. $X_{i,\,j}$ is the normalized value of variable i for a given CBG in city j. $x_{i,\,j}$ is the value of variable i for a given CBG in city j. $x_{min\,i,\,j}$ is the minimum value of variable i for all CBGs in city j. $x_{max\,i,\,j}$ is the maximum value of variable i for all CBGs in city j. For racial groups that are negatively linked to COVID-19, we used the following linear standardization formula with the same descriptions (Eq. 2):

$$V_i = \frac{X_{imax} - X_i}{X_{imax} - X_{imin}} \quad (2)$$

We then combined the top quartile (top 25% normalized values) of RV and green space to determine their corresponding overlaps. We showed four different combinations: high–high, high–low, low–high, and low–low. The last class low–low represented the remaining 75% outliers that were considered low concern.

Statistical analysis

We conducted Hot Spot Analysis (Getis-Ord Gi*) on ArcGIS Desktop (ArcMap 10.8.1) to identify statistically important areas. The Getis-Ord Gi* statistic is calculated by the Hot Spot Analysis tool for each

Table 3 Data and data sources

Data	American Community Survey (ACS)	COVID-19	Green space layers
Year (s)	2018 (5-Year estimates)	2020	2020
Type (s)	Survey	Summary	Vector
Variable (s)	% White population	COVID-19 cases	Parks
	% Black population		Trails
	% Asian population		Wetlands
	% Hispanic population*		Beaches
	% Native population**		
Purpose	Combine and calculate racial vulnerability (RV)	Summarize COVID-19 cases	Combine and calculate green space availability
Source	US Census Bureau	State Health Departments	City and State GIS Departments

*Hispanic = Non-white Hispanic

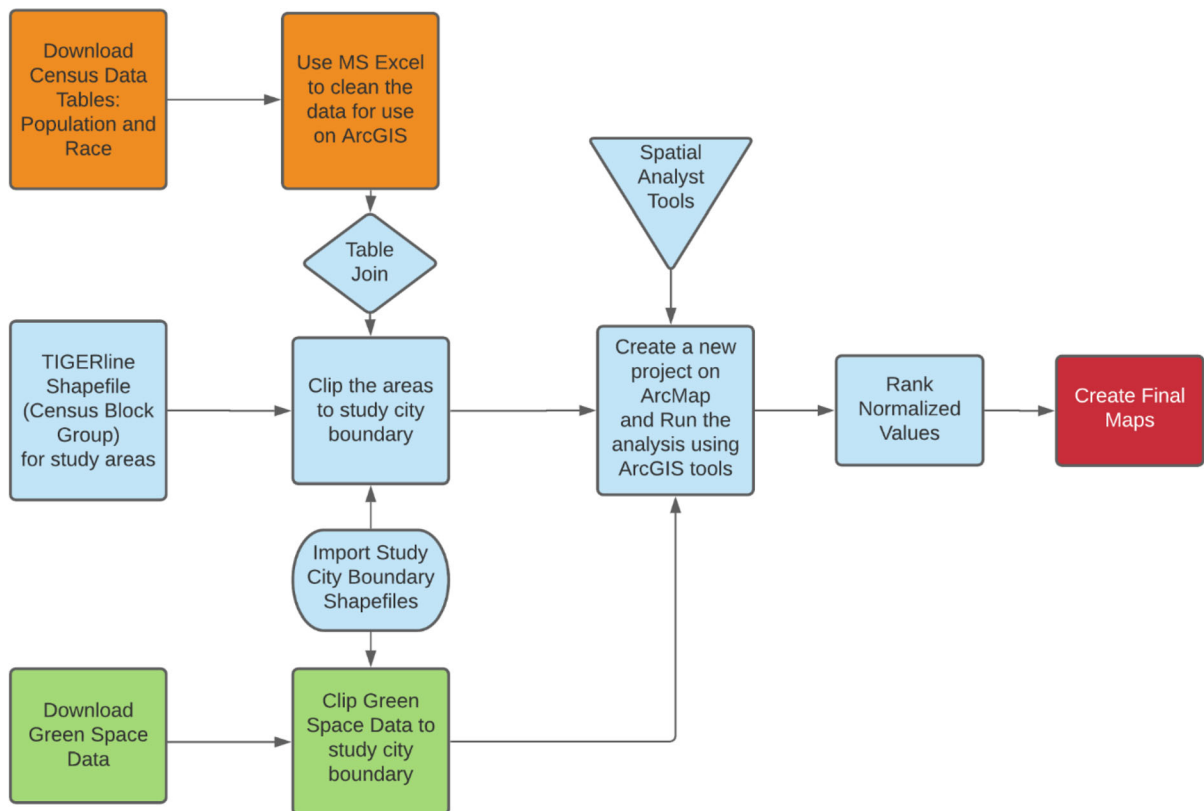**Native = American Indian & Alaska Native + Native Hawaiian and Other Pacific Islander Population

Fig. 3 Spatial analysis flowchart

feature in a dataset. The z-scores and p-values that follow indicate where features with high or low values cluster spatially. This tool works by analyzing each element in the given context of its surroundings (Getis & Ord, 1992; Ord & Getis, 1995). A high-value feature is not automatically assumed to have statistical significance. To be a statistically significant hot spot, a feature must have a high value and be surrounded by other features with high values as well. By definition, a hot spot is a high cluster area, whereas a cold spot is a low cluster area of a particular data set. We used an average of 2000 m distance threshold for running the hot spot analysis. We also tested spatial autocorrelation of how one object measures to the other over a given space (Moran, 1950). This test determines whether the dataset has a clustering, random, or scattered distribution.

Results

Census block group analysis results

We observe high RV in Anchorage on the north and east sides of Downtown Anchorage, as well as around Anchorage Airport in the center (Fig. 4). Meanwhile, the majority of the south side has a low level of RV. Green spaces, on the other hand, are abundant in Anchorage Municipality's south, west, and east sides (Fig. 4). The hotspot results for RV data (Fig. 4) identify neighborhoods in the north as having high RV clusters, while neighborhoods in the south are recognized as coldspots, indicating low vulnerability clusters. The green space hotspot results are not detailed here (Fig. 4), however, they reveal a general clustering to the south of the city municipality. We find a negative correlation (Table 5) between high RV and green space availability using the Pearson correlation test (r = −0.145, p < 0.01). This suggests that, to a

Table 4 Relative racial vulnerability variables' relationship to COVID-19

Variable	Hypothesized relation	Justification	References
Percent White Population (RV1)	Negative (−)	High white population makes a place less vulnerable to COVID-19; white people have second-lowest number of infections of and deaths per capita across the U.S	Simons et al. (2018), Stokes et al. (2020), Killerby et al. (2020), Gold et al. (2020), Price-Haywood et al. (2020), Millett et al. (2020), Garcia et al. (2020)
Percent Black Population (RV2)	Positive (+)	High black population makes a place more vulnerable	Simons et al. (2018), Garcia et al. (2020), Millett et al. (2020), Price-Haywood et al. (2020), Stokes et al. (2020)
Percent Asian Population (RV3)	Negative (−)	Asians have the lowest per capita infections and deaths across the US	Gold et al. (2020), Killerby et al. (2020), Stokes et al. (2020)
Percent Hispanic Population (RV4)	Positive (+)	High Hispanic population makes a place more vulnerable	Garcia et al. (2020), Stokes et al. (2020), Killerby et al. (2020)
Percent Native Population (RV5)	Positive (+)	Native population has the highest per capita infections and deaths across the US	Simons et al. (2018), Stokes et al. (2020), Millett et al. (2020)

certain extent, the availability of green places decreases as RV increases (Fig. 5).

In Portland, north (along the Columbia River), northeast, and southeast sides of Portland have a high RV. On the other hand, low RV exists on the city's west side/Willamette River, and southwest side (Fig. 4). The hotspot findings support this finding of RV (Fig. 4). Portland's green space hotspots are primarily on the west side, with cold spots in much of the city center. A small area of green space hot spot in the southeast corner stands out as an exception. In Portland also, we observe a negative correlation (Table 5) between high RV and green space availability using the Pearson correlation test (r = −0.193, p < 0.05), signaling a scarcity of green spaces as RV increases.

In Phoenix, high RV can be found on the west side and in the vicinity of the airport. Most of the north side and the south mountain in the south side have low RV. This pattern of RV is confirmed by the hotspot results (Fig. 4). The distribution of green areas in Phoenix is noteworthy, with three distinct hot spots intersecting with low racial vulnerable hot spots, followed by a strong display of cold spots in high racial vulnerable hot spots. Green space is abundant on the north, center, and south mountain areas. We find a negative correlation (Table 5) between high RV and green space availability using the Pearson correlation test (r = −0.121, p < 0.05), indicating that the availability of green places decreases as RV increases (Fig. 5).

We see substantial RV in Atlanta's south, southwest, and west sides. The majority of the north side has a low level of RV. The RV hotspot results (Fig. 4) clearly define clusters of high RV in the south, with cold spots in the north indicating low RV there. Two of the three ZIP codes, 30,318 and 30,331, have reported the majority of the COVID-19 infections and deaths in Atlanta; a number (46% of the high RV) of block groups with high RV fall within these two ZIP codes (Fig. 4). Atlanta's green spaces are distributed randomly. We don't notice a clear pattern, however, some of the green spaces that have recently appeared in the south have contributed to the gentrification phenomenon there (Immergluck & Balan, 2017). The hot spot results for green spaces (Fig. 4) support this interpretation by revealing no distinct hot spot or cold spot clusters. We do not find a significant correlation (Table 5) between RV and green space availability in Atlanta.
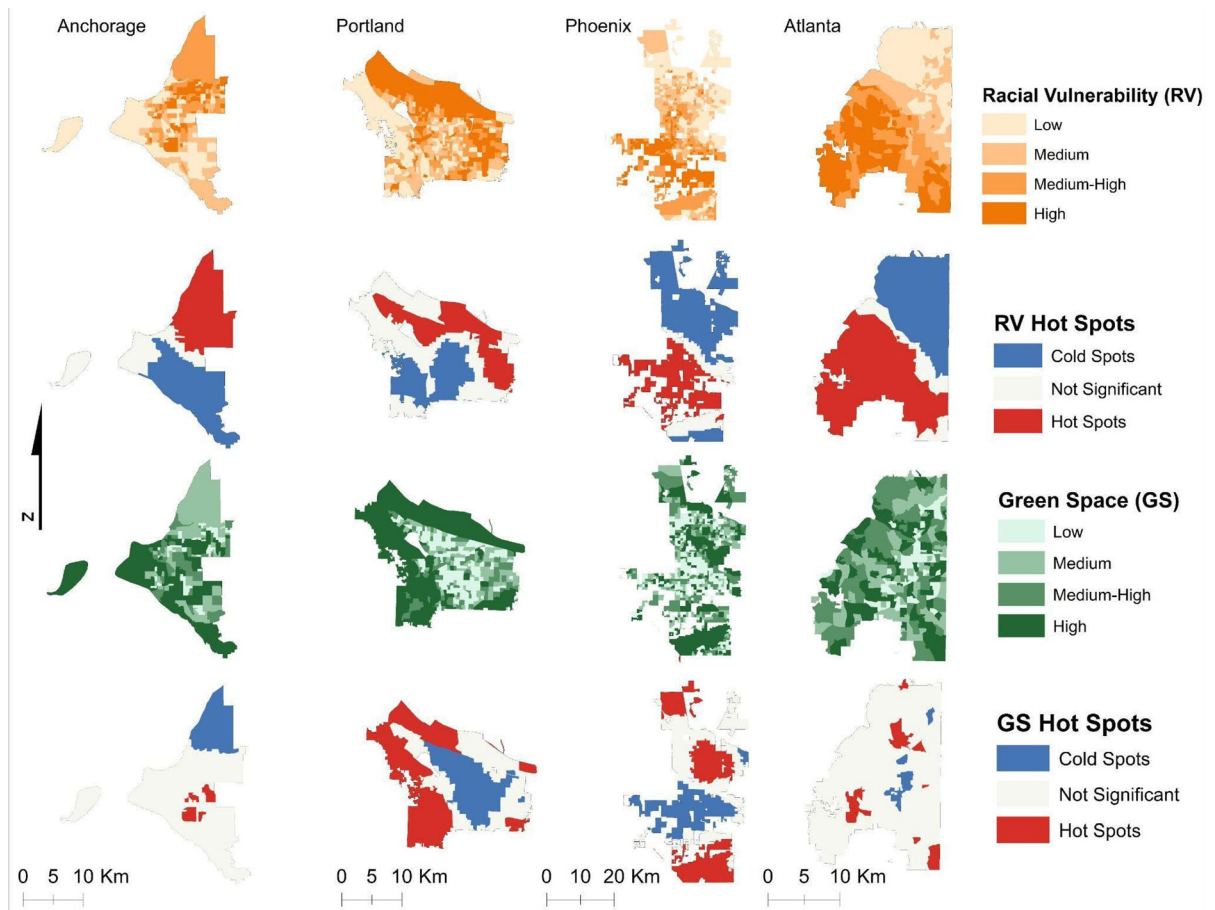
Fig. 4 Racial vulnerability, green space, and their corresponding Hot Spots' distribution in study cities

Table 5 Pearson's correlation coefficients among different combinations of variables (RV and green space) in Anchorage, Atlanta, Phoenix, and Portland. The variable n indicates the number of census block groups included in our analysis of each city

Study city	Correlation	Global Moran's I result
Anchorage $n = 187$	− 0.145*	Clustered
Atlanta $n = 302$		Only Racial Vulnerability clustered
Phoenix $n = 871$	− 0.121**	Clustered
Portland $n = 449$	− 0.193**	Clustered

**Indicates $p < 0.01$; *Indicates $p < 0.05$; Blank cells indicate $p \geq 0.05$

ZCTA analysis results

In Portland, the east side has a high racial vulnerability to COVID-19 (Fig. 6). The west and south of Portland have low racial vulnerability. The hot spot findings further support this observation. The postal code areas generally demonstrate similar trends as CBGs in green space distribution, with high density of green spaces in the southeast and southwest corners of the city. The hot spots of green spaces in the city, however, indicate a stronger presence in the southwest and towards the center. Nine of the ten zip codes in Portland with the highest COVID-19 incidences, all in the north or east, contained high RV and low green space availability
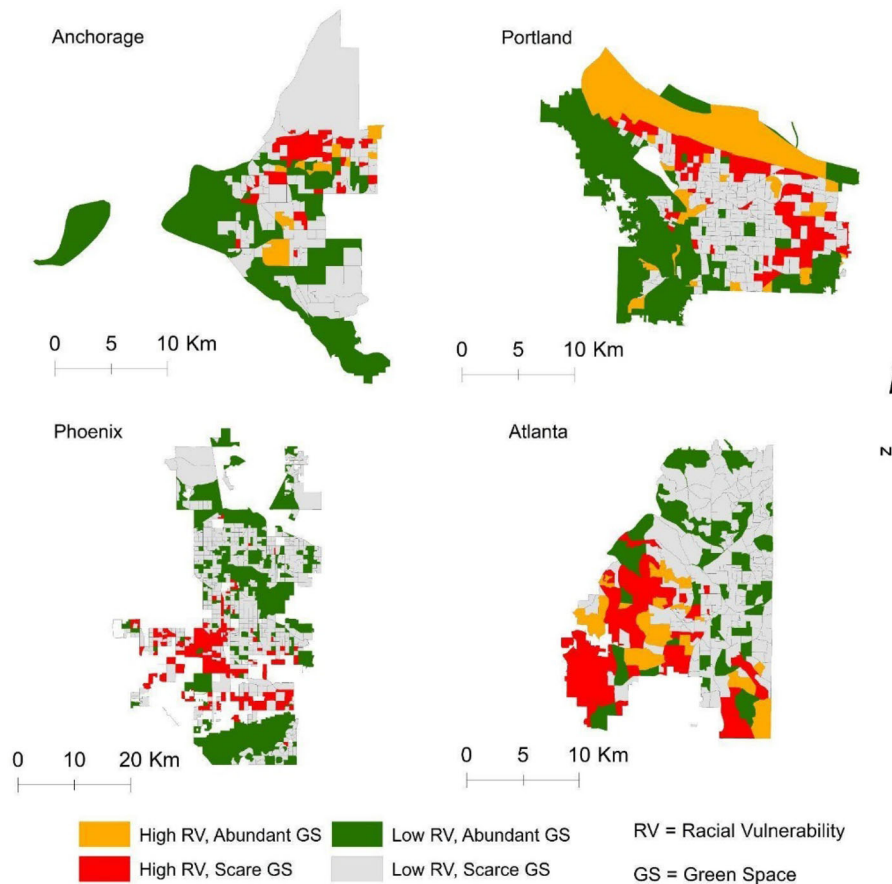
Fig. 5 CBG Vulnerability map showing the overlaps between RV and green space

areas. We see a positive correlation between COVID-19 numbers and racial vulnerability using the Pearson correlation test ($r = 0.796$, $p < 0.01$, Table 6); other relationships are not significant in Portland at the ZIP code level.

In Phoenix, the south and center areas have a high racial vulnerability to COVID-19, and this observation is supported by the hot spots analysis (Fig. 7). The postal codes in the north have a low racial vulnerability. The green space in the city has two hot spots, one in the center-north and another one in the far south. The cold spots of green space are in the southwest and center ZIP code areas. Nine of the top ten zip codes with the highest number of COVID-19 cases, all in the south or west, have a high RV and a scarcity of green space. Like Portland, we also see a positive correlation between COVID-19 numbers and racial vulnerability using the Pearson correlation test ($r = 0.444$, $p < 0.01$, Table 6); the only other significant

relationship is found between racial vulnerability and green space availability ($r = 0.387$, $p < 0.01$).

Discussion

Spatial patterns of racial vulnerability and green spaces

Like many other urban areas in the United States, Anchorage has, historically, seen a concentration of poverty and RV in areas near the center of the city where, traditionally, there has been little green space. In the case of Anchorage, the location of a large military base to the north of the city, and along the urban edge, has further impacted access to green space in several key neighborhoods. To the east and south of Anchorage, the city limits end where the second-largest state park in the United States begins and
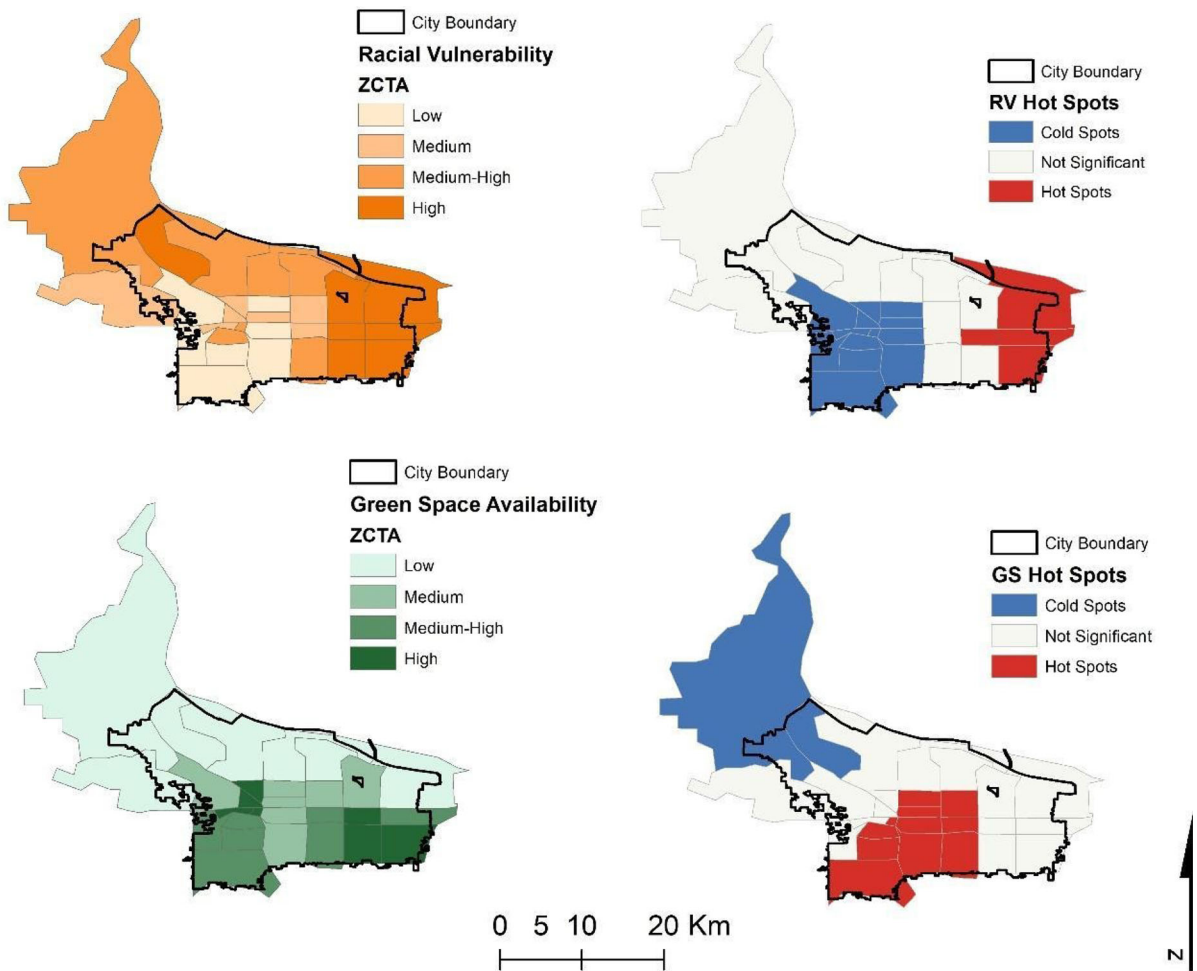
Fig. 6 ZCTA-level maps showing racial vulnerability, green space density, and their corresponding hot spots for Portland

Table 6 Pearson's correlation coefficients among different combinations of variables in Portland and Phoenix

Study city	Variables correlated	Correlation	Global Moran's I result
Portland $n = 27$	COVID-19 count versus Racial Vulnerability	0.796**	Clustered
	COVID-19 count versus Green Space Availability		Clustered
	Racial Vulnerability versus Green Space Availability		Clustered
Phoenix $n = 66$	COVID-19 count versus Racial Vulnerability	0.444**	Clustered
	COVID-19 count versus Green Space Availability		Clustered
	Racial Vulnerability versus Green Space Availability	0.387**	Clustered

The variable n indicates the number of census block groups included in our analysis of each city

**Indicates $p < 0.01$; *Indicates $p < 0.05$; Blank cells indicate $p \geq 0.05$

Bureau of Land Management lands and coastal areas are found. Neighborhoods in much of this area are populated by a more racially homogenous and white

population that has taken root in a large suburban area known as the "Hillside", where developments and zoning requirements have generally led to upper-
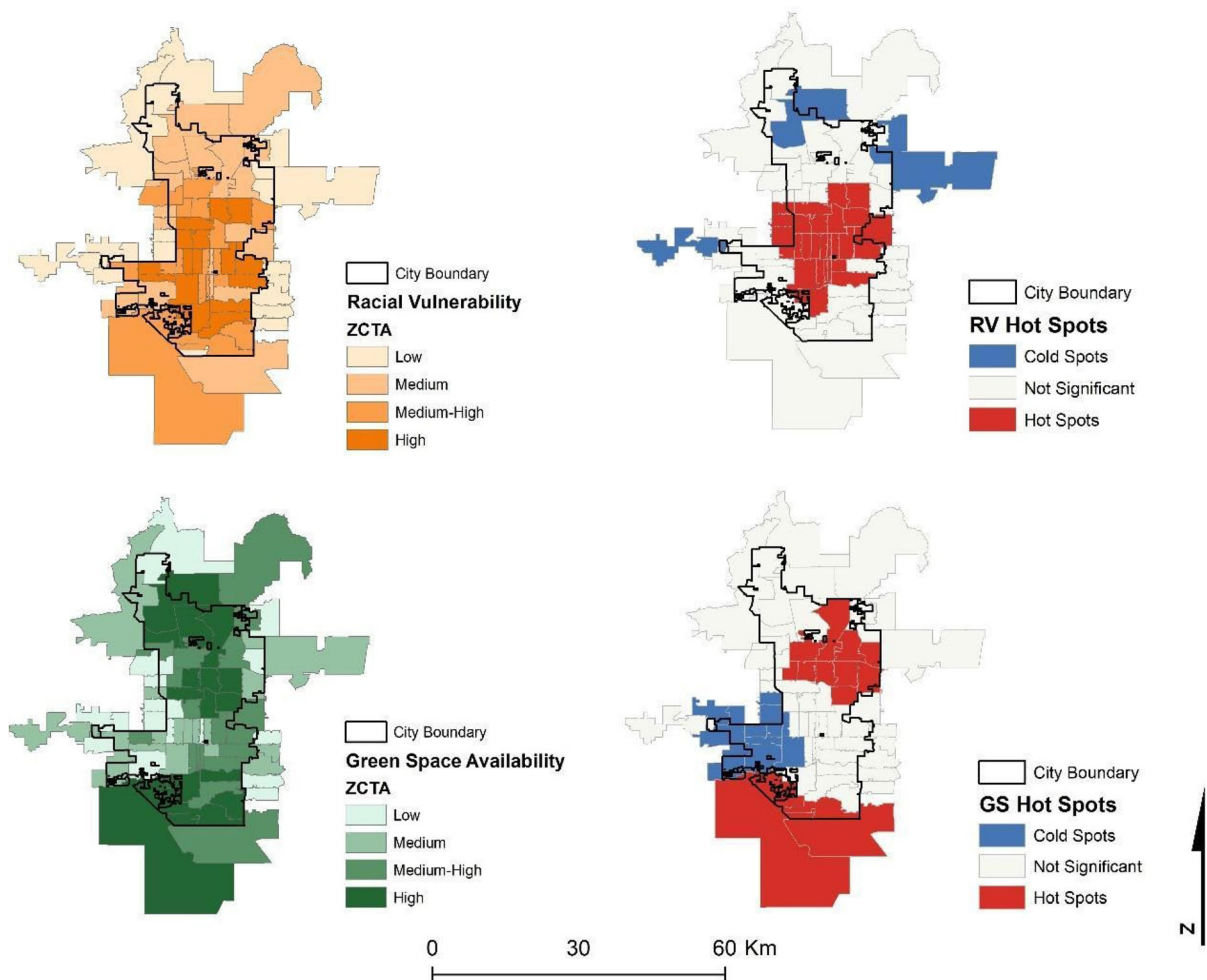
Fig. 7 ZCTA-level maps showing racial vulnerability, green space density, and their corresponding hot spots for Phoenix

middle-class housing construction. Similarly, the west of Anchorage has access to a large park area carved out of a decommissioned military base after World War II (Pallathadka et al., 2021). These suburban areas developed at a time when park planning and public interest in preserving green spaces was high. In more urban areas, where zoning and historical development favored more intense urban uses, access to green space is more limited and coincides closely with indices of high RV. That said, municipal park planners and agents of conservation organizations have worked hard to extend public parks and access to green spaces in underserved parts of the municipality. Particular success is found in the extension of a network of trails and parks in Anchorage's "Midtown" along creek bottoms and the coast.

Portland is one of the whitest cities in the United States, and this is not by chance. Following WW2, discriminatory measures such as redlining and gentrification ensured that people of color were pushed east of the Willamette River (Billings Jr, 2000; Hannah-Jones, 2010). One of the reasons people of color attempted to relocate to the Portland area in the first place was to work on the city's flourishing industrial landscape, which included a busy river port (Semuels, 2021). In the 1950s, Interstate-205, then on the outskirts of Portland, was developed as a bypass for Interstate-5. This area, surrounding the Interstate-205, evolved into black and brown neighborhoods, the legacy of which can still be seen today. For decades, these neighborhoods were neglected and underinvested (Hannah-Jones, 2010). Portland saw a new

economic boom in the 1990s with technology and manufacturing, and many young people relocated there, bringing a new wave of gentrification with them. The new technology wave primarily benefited white and Asian populations, but it had little impact on black and brown groups. Asians continue to have the most income inequality as a group in the US, yet relatively higher-earning Asians have been able to migrate into white neighborhoods in the Portland region (Kochhar & Cilluffo, 2020). Since the 1990s, significant city investments in green spaces have gentrified several neighborhoods, mainly those that were historically non-white. According to one report, Portland is the fourth fastest gentrifying city in the United States (Homes & Gardens of the Northwest staff, 2017).

Phoenix has a sizable Hispanic (43%) and Black (7%) population, and the city has always had people of color since its foundation; nevertheless, the city's urban planning is also a story of segregation (Harvey, 1996; Bolin et al., 2005). Because of the flooding of the Salt River in the nineteenth century, whites began to migrate northward, forcing the areas between the CBD and the Salt River to lean industrial and form temporary ghettos. Communities of color began to concentrate in South Phoenix, where the majority of the industries thrived. Minorities in South Phoenix have been deprived of their fair share of urban resources as a direct result of urban policies (Bolin et al., 2002, 2005). Although the lack of sufficient green spaces in these neighborhoods has historical roots, present challenges stem from the industrial landscape and gentrification risks. The City of Phoenix is actively working on a South Phoenix Development Plan, which includes plans for improved mobility (Taros, 2021).

Atlanta is one of the few large cities where the black population exceeds 50% of the total population, however, there are significant inequities in Atlanta's black-majority society. According to the 2018 American Community Survey conducted by the United States Census Bureau, Atlanta has the highest average household income inequality (Lu & Tanzi, 2019). The majority of Atlanta's black, Hispanic, and other native communities have traditionally lived in the city's south and west sides, but these areas have suffered from decades of urban mismanagement. However, recent large-scale developments over a short period of time have made it difficult for long-term inhabitants to keep their homes. The Atlanta Beltline is a prime

example of such initiatives, with property values increasing 17.9 percent to 26.6 percent closer to the Beltline between 2011 and 2015, depending on the stretch of the Beltline (Immergluck & Balan, 2017). Redlining, as in other cities, has played a significant part in white communities settling on the north side. Asians have gradually moved to the north side. However, past segregation has significantly contributed to today's RV distribution.

Green spaces in COVID-19 context

Green spaces are constructed for a variety of purposes, but it is a novel idea to see them as a space that may promote recreation while also enabling social distancing. In the case of Anchorage, prior research found a significant link between park size and the diversity of park values (Brown, 2008). In times of pandemics such as COVID-19, Anchorage's relatively larger green spaces can thus ideally serve all groups, vulnerable included, to adequate recreation if such green spaces are located in an equitable manner. However, some of Anchorage's green spaces, such as Kincaid Park, Chugach State Park, and Far North Bicentennial Park are relatively inaccessible by public transportation; the city can enhance access by providing public transportation as well as information.

There are several green spaces in Portland, including parks, trails, and wetlands, but they are not equally distributed over space. Many of the city's green spaces in the northeast and north are adjacent to industrial parks, making them undesirable for recreation in several sections (Stroud, 1999). Because COVID-19 hot spot areas in Portland generally overlap with industrial parks, the practical recreational use of those parks may be minimal. Furthermore, Forest Park in Portland's northwest section is inaccessible by public transportation, leaving it solely accessible to people who own automobiles. This makes it difficult for vulnerable populations to benefit from Forest Park's large network of trails and green open space. The lesson from Portland is that cities should build parks that serve everyone and provide meaningful access, rather than offering symbolic services.

The climate influences how green and open areas are developed in Phoenix. However, many of the open areas, such as North Mountain and South Mountain parks, primarily serve wealthy neighborhoods with greater access, often by foot and bicycle, while

offering minimal public transportation for residents from other parts of the city (Hoover et al., 2021). With new green space installations, the underprivileged areas in this city have often suffered from gentrification (Richardson et al., 2020); improved stakeholder involvement and community outreach would help to prevent gentrification while also increasing green and open spaces.

For years, Atlanta has had inadequate green space management; numerous non-profits operate in the Atlanta region to improve the issue and better manage the existing parks and open spaces (Watkins et al., 2018). Nevertheless, new improvements come with the threat of gentrification (Immergluck & Balan, 2017). Atlanta's green space problem is multi-faceted—there is the problem of creating adequate green space, and then there is the challenge of expanding access to existing green spaces.

Environmental justice

This study describes the spatial patterns of racial demographics of four distinctly different cities across the United States, while associating spatial variability of green spaces in these cities. Our results indicate that none of the four cities in this study have sufficient green spaces in CBGs and ZCTA predominantly occupied by people of color. Our study compliments several other environmental justice studies since the onset of COVID-19 pandemic that have demonstrated the disproportionate distribution of resources. Although the RV concept introduced in this study is novel and specific to the ongoing pandemic's impact, it has existed from an environmental justice perspective for decades (Taylor et al., 2007; Boone et al., 2009; Rigolon & Németh, 2018).

During the pandemic, we saw an increased usage of these urban green spaces as they offered opportunities of physical and mental well-being, while following social distancing guidelines. A study conducted by University of Vermont enumerates benefits of green spaces that extend beyond health and well-being (Grima et al., 2020). Therefore, expanding green space coverage and accessibility would contribute to mitigating not just the present pandemic, but also future pandemics (Tribby & Hartmann, 2021; Lu et al., 2021). The lack of adequate green spaces in Phoenix, for example, has been an issue even before the pandemic, as suggested by Truman (2014). Park and

Guldmann (2020) study disparities in community green space accessibility in Atlanta and also find similar results to our study. Another example of a study related to spatial distribution of urban resources is Karaye and Horney (2020) who conclude that COVID-19 infection rates in the US have been influenced by minority status, household composition, housing status, and disability. These studies provide empirical evidence for policy makers to re-think urban zoning and increase the proximity of communities of color to urban green spaces.

Limitations

We are aware, like with other works, that our research has limitations. We proposed a framework in which Asians and whites are less vulnerable to COVID-19. This trend may or may not change as the pandemic progresses and eventually concludes. As a result, the contribution of this study is not necessarily identifying who is always vulnerable, but rather relating it to what resources are available to those who are highly vulnerable at any given time. Our framework would aid in the assessment of excessive and inadequate resource distribution between demographic groups; we propose that such distributions be fair and appropriate. This is not a study to recommend a specific set of indicators. Instead, we are exploring how GIS can be used to combine social and ecological factors for a given geographic area with a framework founded on RV patterns exhibited by the COVID-19 pandemic. Hence, this is a demonstration of how social and ecological factors can be effectively used to identify potentially problematic areas during a pandemic for the just allocation of resources.

Aside from race and ethnicity, poverty, income, immigration status, and language proficiency can all have an impact on the population during a pandemic. From the standpoint of ecological variables, climatic factors such as temperature, precipitation, and humidity may play a role in the spread of COVID-19, however research on this topic is limited. Climate suitability could also be the deterministic driver of COVID-19 spread. Future research could delve into some of these relationships in order to better inform urban planners and policymakers.

In addition to the limitations stated above, there are certain data limitations. For example, Anchorage has not yet made its COVID-19 data available at zip code-

scale owing to privacy concerns, as Anchorage Municipality has a very low population density. In Atlanta, two of the zip codes with the highest infection rates comprise nearly all our racially vulnerable block groups, but the comprehensive zip code data here is lacking for further comparisons (Raymond, 2020).

Conclusions

Green spaces are normally considered to improve a neighborhood's health and well-being. Pandemics like COVID-19 highlight a gap in urban park placement. Inequality exists in public spaces, both in terms of access and amenities. Parks and trails are examples of public spaces where social distancing is possible, and the risk of infection is low. In our study, we analyzed RV at the CBG and ZCTA scale and related it to the availability of public green spaces. We discovered disparities in the distribution of public green space in all four study cities, and the findings of our study emphasized the legacy of historical issues in urban planning. The recurrent theme we find in our results in the context of COVID-19 is that people of color experience a disproportionate impact from COVID-19, and they also have substantially fewer green open areas for recreation. In Portland and Phoenix, we found that COVID-19 cases follow the RV framework, and more COVID-19 cases occurred in racially vulnerable CBGs and ZCTAs. This shows that urban policies have a far-reaching impact that extends well beyond initially perceived injustices. While these policies cannot be drastically changed, and parks cannot be built quickly, understanding social constraints and ecological repercussions can help urban planners take tangible steps toward solutions. Cities would do well to guarantee that vulnerable communities have access to sufficient amounts of green space.

The importance of our study stems from the fact that public green spaces have societal value. Although the benefit may be intangible to ordinary people in day-to-day life, recent events involving lockdowns, masking, and social distance protocols clearly highlight the need for activities such as walking, inhaling fresh air, and simply being outside. The pandemic and subsequent lockdowns highlighted the importance of public open places across the world. In the future, while designing new green areas, planners and policymakers must consider RV as well as physical and mental health repercussions.

Authors' contributions AP Conceptualization, Methodology, Software, Formal Analysis, Investigation, Visualization, Writing—Original Draft, Review, & Editing. LP Conceptualization, Methodology, Formal Analysis, Investigation, Writing- Original Draft, Review, & Editing. SR Methodology, Formal Analysis, Investigation, Writing—Original Draft, Review, & Editing. HC Conceptualization, Writing—Review & Editing, Supervision. DVD Writing—Original Draft, Review & Editing.

Availability of data and material The data that support the findings of this study are available from the corresponding author, AP, upon reasonable request.

Declarations

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

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