J Urban Health (2023) 100:686–695
https://doi.org/10.1007/s11524-023-00748-5

ORIGINAL ARTICLE

Does Urban Greenspace Reduce Mortality Inequalities Based on Poverty, Race, or Both in Philadelphia, PA?

Leah H. Schinasi · Michelle C. Kondo · Janelle Edwards · Jane E. Clougherty · Anneclaire J. De Roos · Usama Bilal

Accepted: 6 June 2023 / Published online: 10 August 2023

Abstract While past research suggests that urban greenspace is associated with weaker income-based mortality inequities, little is known about associations with racial inequities, which may be distinct owing to historical and contemporary forms of racism. We quantified the extent to which different measures of greenspace modified socioeconomic and racial/ethnic inequities in all-cause and cardiovascular disease mortality. For every residential census tract in Philadelphia, PA (N = 376), we linked counts of all-cause and cardiovascular mortality (years 2008–2015) with measures of greenspace (proportion tree canopy or grass/shrub cover, proportion residents reporting park access, and the normalized difference vegetation index measure of overall greenness) and American Community Survey-based measures of sociodemographic composition (proportion of residents living in poverty, proportion identifying as non-Hispanic Black, and the index of concentration at the extremes (ICE) representing racialized economic deprivation). We used age- and sex-adjusted negative binomial models, with the natural logarithm of age-specific population counts as an offset, to quantify the magnitude of inequities by each composition variable, overall and stratified by categories of each greenspace measure. Inequities in mortality were weaker among neighborhoods with higher proportion grass/shrub cover or overall greenness. The most substantially narrowed inequities were those by the ICE. Mortality inequities did not differ substantially by perceived park access, and tree canopy was associated with weaker ICE-based inequities only. In this ecologic analysis, neighborhood greenspace was associated with weaker mortality inequities. However, associations varied across greenspace type and sociodemographic composition metrics, with generally stronger associations with overall greenness and grass/shrub coverage, and for ICE-basedinequities.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11524-023-00748-5.

L. H. Schinasi (✉) · J. Edwards · J. E. Clougherty · A. J. De Roos
Department of Environmental and Occupational Health, Dornsife School of Public Health, Drexel University, Philadelphia, PA, USA
e-mail: lhs36@drexel.edu

L. H. Schinasi · J. Edwards · J. E. Clougherty · A. J. De Roos · U. Bilal
Urban Health Collaborative, Dornsife School of Public Health, Drexel Univeristy, Philadelphia, PA, USA

M. C. Kondo
USDA Forest Service, Northern Research Station, Philadelphia Field Station, 100 North 20th Street, Suite 205, Philadelphia, PA 19103, USA

U. Bilal
Department of Epidemiology and Biostatistics, Dornsife School of Public Health, Drexel Univeristy, Philadelphia, PA, USA

Keywords Green space · NDVI · Mortality · Equigenic · Inequities · Index of concentration at the extremes

Introduction

Worldwide, cities are investing in greenspace—creating parks and planting trees—to promote health. A growing body of evidence suggests that greenspace is associated with lower risk of premature mortality and various morbidity outcomes [1] and may improve health through a multiple pathways, including reducing stress, bolstering mental health, promoting physical activity, and/or reducing environmental stressors, such as noise or heat [2].

Perhaps, even more compelling is a small literature suggesting that greenspace may reduce health inequities [3–5]. Indeed, lower income populations may have more to gain from greenspace as compared to their wealthier counterparts [6]. For example, the cooling properties of greenspace on hot days may be more beneficial to residents who are unable to afford air conditioning [7]. In addition, in contrast to other health promoting assets that may require payment and thus exclude lower income community members (e.g., healthy food stores, gyms), greenspace is often freely available to the public.

The term "equigenesis" was introduced in 2008 to describe the idea that environmental interventions may be used to promote health equity [6]. Equigenesis may be achieved by promoting the health of less advantaged people or groups equally (or more) than advantaged ones (i.e., "levelling up"), or by limiting the health of advantaged people or groups to a greater extent than that of less advantaged ones (i.e., "levelling down"). To date, little research on the "equigenic" potential of greenspace has been conducted in the USA, despite the country's pervasive and geographically patterned health inequities [8]. Further, few studies have empirically assessed the association of greenspace with racialized or racialized economic health inequities—which may be distinct from relationships with income-based inequities. This is important, because racism in the USA, which manifests at different levels, has implications for greenspace availability, quality, and utilization in racially minoritized communities [9, 10]. For example, structural racism in the form of historical redlining and present-day racial residential segregation may impact greenspace availability or quality in marginalized communities [11–13]. Experiences of racial discrimination in green spaces—a form of personally mediated racism—may impact greenspace utilization in minoritized communities [14].

Here, we quantified inequities in neighborhood rates of all-cause and cardiovascular mortality. We first calculated inequities using neighborhood composition measures based on poverty, race/ethnicity, and racialized economic deprivation. We then calculated the extent to which different measures of greenspace narrow (i.e., modify) these inequities. We hypothesized that greater availability or perception of greenspace would be associated with weaker neighborhood-level inequities in mortality rates. However, we also hypothesized that racism-mediated mechanisms would limit the benefits of green spaces in neighborhoods with higher proportion racially marginalized residents. Thus, we hypothesized that impacts of green spaces on reducing inequities would be less substantial for race-based, rather than poverty-based inequities. Finally, we hypothesized that greenspace types that do not require active utilization, such as trees or grass rather than parks, would be most effective at narrowing inequities. We conducted this analysis in Philadelphia, PA, one of the poorest and most racially segregated cities in the USA, one where institutional racism is associated with present-day inequities in tree coverage [15] and also one with extensive green areas, including both natural and planned parks, but also sections with high amounts of impervious land cover [16].

Methods

In this ecologic analysis, the unit of observation was 2010 census tracts, which we used to approximate neighborhoods. Census tracts are administrative units, defined by the U.S. Census Bureau and often used in population-health research to approximate neighborhoods [17]. Of 384 total census tracts in Philadelphia, we excluded 8 non-residential areas, leaving 376 units in the analysis. Although there are many ways in which the geographic boundaries for a neighborhood can be identified, census tracts are most commonly used to approximate neighborhoods [18]. Thus, using the census tract, rather than census blocks or census block groups, allows greater comparability across studies. Census tracts are also socially homogeneous and, in past research, have been shown to perform as well as census block groups for monitoring inequities in mortality rates [19].

Data

We calculated total counts of deaths from all causes and from cardiovascular disease (CVD, ICD-10 codes I00-I99) in each census tract, stratified by categories of sex and age (< 18, 18–44, 45–64, 65+) in years 2008–2015 in Philadelphia. Mortality data came from the Bureau of Health Statistics and Registries of the Pennsylvania Department of Health, Harrisburg, Pennsylvania. We linked these with tract-level sex- and age-stratified population counts. In addition, we linked these with data on proportion of census tract residents living in poverty, proportion non-Hispanic Black, and population density (count/km^2). The census tract level population and demographic composition data came from 5-year average estimates of the US Census Bureau's American Community Survey (ACS, years 2011–2015) [20]. We also used ACS data on median household income and proportion non-Hispanic Black to calculate the index of concentration at the extremes (ICE) as a measure of racialized economic deprivation. The ICE quantitatively reveals spatial polarization of deprivation [21], comparing concentrations of low-income Black residents with concentrations of high-income White ones. By incorporating race and income into a single measure, the ICE also accounts for the entanglement of poverty and the social construct of race in the USA [21]. The ICE ranges in value from −1 (most deprived) to 1 (most privileged). We calculated the ICE statistic using methods used by others (Supplemental Materials 1) [21].

Greenspace Measures

We linked the data with tract-level measures of overall greenness, proportion tree canopy, proportion grass/shrub cover, and proportion of adult residents reporting access to a park or open space that they felt comfortable visiting. Tree canopy and grass/shrub coverage estimates were derived from high resolution (30.5 cm × 30.5 cm) orthophotography and Light Detection and Ranging (LiDAR)-based land cover assessment data for the city of Philadelphia, years 2008 and 2018 [22, 23] and calculated as the total land area covered by tree canopy or grass/shrub cover divided by the total land area in each tract. We linearly interpolated across years 2008 and 2018 to derive a year 2013 estimate. We selected year 2013, because it was the median between the years of the two land cover assessments. Linear interpolation has been used previously to derive annual estimates of land cover when data are available for only a few years [24]. The measure of perceived park access was derived from the Southeast Pennsylvania Household Survey (SEPHHS) of a representative sample of the non-institutionalized adult population living in South Eastern Pennsylvania. Survey participants were identified using random digit dialing and asked about health diagnoses, behavior, and neighborhood environment. Proportions of residents reporting access to a park or open space were estimated using responses to the following question in the 2012 SEPHHS: "Is there a park or other outdoor space in your neighborhood that you are comfortable visiting during the day?" Smoothed, tract-level estimates were calculated using Bayesian hierarchical models that simultaneously account for spatial and temporal dependencies [17]. Details on the methods used to derive the smoothed estimates are reported elsewhere [25]. We also measured overall greenness using the normalized difference vegetation index (NDVI), a unitless index ranging from −1 (least green) to 1 (most green). We used cloud-, shadow-, and water-masked Landsat 8 level 2, collection 2, tier 1 atmospherically corrected surface reflectance images, captured between January 1, 2013 and December 31, 2015 to identify the maximum NDVI in each 30 m pixel over the time period [26], and calculated census tract averages of these pixels. We used images from 2013 to 2015 to account for subtle variability in the NDVI that might have occurred because of rainfall or humidity levels. We used Google Earth Engine to retrieve the images, to cloud-, shadow-, and water-mask them, and to calculate the maximum pixel-level NDVI for the time period. We used the Raster package's extract function [27] of the R software (version 3.5.1) to calculate the average NDVI value in each tract; any cell whose center appears within the boundaries of the census tract polygon was included in the calculation.

Analysis

The objective of this analysis was to investigate the extent to which greenspace measures modify associations between neighborhood compositional measures and age- and sex-adjusted mortality rates. That is, we explored whether the association between different measures of deprivation and mortality rates was closer to the null in census tracts with greater amounts of greenspace. Thus, the outcomes in this ecologic analysis were age-, sex-, and census-tract specific mortality counts (all-cause or CVD). The primary explanatory variables were the following: proportion non-Hispanic Black, proportion living in poverty, and the ICE measure of racialized economic deprivation. We explored the greenspace measures as effect modifiers by modeling them in interaction terms. We first estimated associations between each of the sociodemographic variables and the mortality rates using negative binomial models. We rescaled the sociodemographic terms to range from 0 (lowest levels of marginalization) to 1 (highest levels of marginalization). We entered the rescaled measures as continuous terms in our models; preliminary analyses supported the assumption of linearity. In all models, we adjusted for age and sex categories. We also included the natural logarithm of age- and sex-specific population counts as an offset term. In preliminary analyses, we adjusted for population density (modeled as a three-level categorical variable with categories based on tertiles). Because population density did not change the estimates of association between the composition variables and mortality rates, we report results unadjusted for population density. We exponentiated the beta coefficients associated with the composition terms to derive estimates of the relative index of inequality (RII) and its associated 95% confidence interval (CI). The RII is a regression-based relative measure of inequality [28]. Here, it compares rates of mortality in census tracts with the highest vs. the lowest levels of marginalization/deprivation. Next, we explored the greenspace measures as effect modifiers of associations between the sociodemographic composition variables and mortality rates by including an interaction term between each sociodemographic variable and each greenspace measure. Specifically, we used these interaction terms to quantify the extent to which the magnitude of the RIIs differed across tertile-based categories of the greenspace measures. We ran each combination of greenspace/composition variable interaction separately.

Assuming that O_{ias} represents the observed number of deaths occurring in census tract i among individuals in age category a and sex category s, and P_{ias} is the count of individuals in age category a and sex category s living in census tract i and O_{ias} ~. Negative binomial $\log(\mu_{ias} * P_{ias})$, the fitted model, including the interaction terms, took the following form:

$$\log\left(\mu_{ias}\right) = \alpha_0 + \beta_1\text{composition}_i + \beta_2\text{green}_{\text{mod}i} + \beta_3\text{green}_{\text{high}i} + \beta_4\text{composition}_i * \text{green}_{\text{mod}i} + \beta_5\text{composition}_i * \text{green}_{\text{high}i} + \beta_6\text{age} + \beta_7\text{sex} + \log\left(P_{ias}\right),$$

where μ_{ias} is the number of deaths in census tract i belonging to age category a and sex s; the composition variable is either proportion non-Hispanic Black, proportion living poverty, or the ICE statistic for racialized economic deprivation in census tract i; green represents one of the four greenspace measures; sex is a binary indicator, and age is a vector of categorical terms representing the relevant age categories; and population is the count of total population of individuals in tract i belonging to age category a and sex s.

We present results as the RII and their associated 95% CIs, overall, and by tertile-based categories of each greenspace measure (low, moderate, or high). The RII may be interpreted as the linearized mortality rate ratio comparing census tracts at the highest vs. the lowest level of deprivation for each sociodemographic measure. RII values further from 1 represent greater inequities. Because a higher ICE value represents more privilege, and a lower value represents more deprivation, and for this measure, we report the reverse of the estimated RII estimates so that the directionality is consistent with the other measures for which the highest values represent the greatest marginalization. We also calculated the ratio of the RIIs (RRIIs) and associated 95% CI to quantify the magnitude of the difference of the RIIs, comparing associations in the highest vs. the lowest greenspace categories. We calculated the RRII by exponentiating the coefficient associated with the interaction between the highest tertile of greenspace and the sociodemographic variable (β_5 from the model; Supplemental materials 2) [29].

Results

Description of the Study Area

Across 376 Philadelphia census tracts, the median proportion tree canopy and grass/shrub cover were 0.12 (interquartile range (IQR): 0.08, 0.20) and 0.18 (IQR: 0.14, 0.25), respectively (Table 1). Across all census tracts, proportion tree and grass/shrub cover ranged from 0.02 to 0.80 and 0.02 to 0.47, respectively. Proportion of adults reporting park access ranged from 0.45 to 0.95, and NDVI ranged from 0.16 to 0.88 (ranges not shown in table). The tracts were densely populated (median (IQR): 6811.3 population/km^2 [4366.2, 9999.5], Table 1). The median proportion living in poverty was 0.25 (IQR: 0.13, 0.37), and median proportion non-Hispanic Black was 0.30 (IQR: 0.10, 0.80). Greenspace measures were generally higher in areas with a lower proportion of households living in poverty and lower proportion non-Hispanic-Black residents. Population density followed a gradient of increasingly higher population as proportion living in poverty increased. Proportion tree canopy was moderately correlated with proportion grass/shrub cover and perceived park access (*r*: 0.39 and 0.34, respectively) and highly correlated with NDVI (*r*: 0.87, Supplemental Materials 3).

Overall Associations

There were inequities in rates of all-cause and cardiovascular mortality across tract-level measures of poverty and race composition and racialized economic deprivation (Table 2). The magnitude of the inequities, measured with the RII, was similar for all-cause and CVD mortality. Racialized economic deprivation (ICE)-based inequities were most substantial, while race-based inequities were least substantial. For example, compared to census tracts with the least deprivation, quantified using the ICE, tracts with the highest deprivation had 2.91 (95% CI: 2.67–3.18) times the rate of all-cause mortality and 2.86 times the rate of CVD mortality (95% CI: 2.58–3.17).

Modification of the RII by Greenspace Measures

Figure 1 shows poverty-, race/ethnicity-, and ICE-based RII estimates for all-cause mortality, stratified by tertiles of the greenspace measures (Supplemental Material 4 shows point estimates and RRIIs). Patterns for CVD mortality were similar and are illustrated in Supplemental Materials 5. Consistent with the equigenic hypothesis, the RIIs representing associations of poverty or racial/ethnic composition and ICE with rates of age- and sex-adjusted mortality were weaker in tracts with higher proportion grass/shrub cover or overall greenness. These trends are represented by a gradient of increasingly smaller RII estimates, moving from the lowest to the highest category of greenspace. The most substantially weakened associations were for ICE-based RIIs. For example, the ICE-based RII for all-cause mortality was 4.17 (3.57–5.00), 3.12 (2.63–3.70), and 1.92 (1.64–2.27) in tracts with low, moderate, and high proportion of grass/shrub cover, respectively. Based on the RRII, the ICE-based RII was 51% lower (95% CI: 0.39–0.62) in tracts with the highest vs. the lowest greenness levels and 54% lower (95% CI: 0.37–0.57) in tracts with the highest vs. the lowest proportion grass/shrub cover (Supplemental Table 4). We did not observe a trend of consistently weaker inequities as proportion tree canopy or proportion residents reporting park access increased. However, ICE- and poverty-based inequities in all-cause mortality rates were weaker in neighborhoods with the highest proportion tree canopy cover.

Discussion

Increasingly, cities are using greenspace interventions to promote health and equity; understanding the types of greenspace that provide the greatest benefits is critical. This analysis contributes to understanding of the equigenic potential of greenspace by considering associations with racial and racialized economic inequities, by evaluating associations with different greenspace types, including a measure of perceived access to parks or open spaces, and by investigating these hypotheses in a major USA city. We found that the magnitude of the inequities in rates of mortality across Philadelphia was less substantial in census tracts with higher overall greenness (NDVI) and higher proportion grass/shrub coverage. The narrowing trend was most pronounced for racialized economic deprivation-based inequities. These results contribute evidence in support of the equigenic hypothesis for greenspace and suggest that the

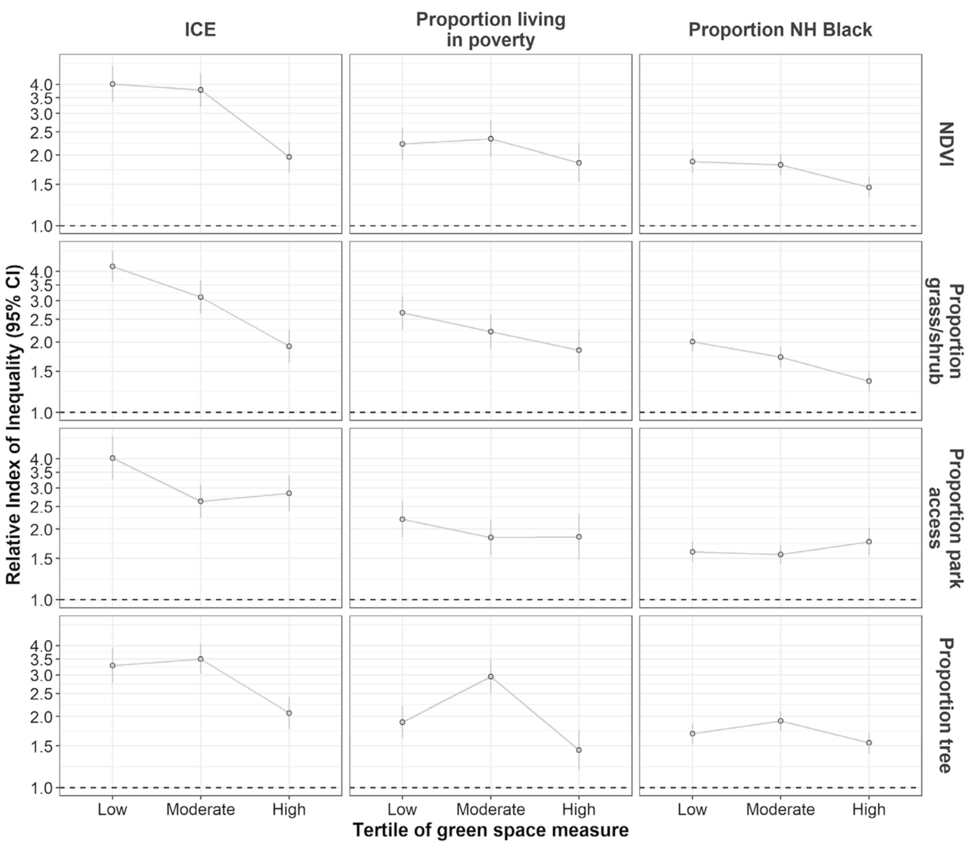
Table 1 Environmental and contextual characteristics of the 376 Philadelphia census tracts included in this analysis, overall, and stratified by tertile-based categories of proportion of residents living in poverty, proportion of non-Hispanic Black, and the Index of Concentration at the Extremes (ICE) statistic representing racialized economic deprivation

	All tracts	Proportion living in poverty			Proportion NH Black			Racialized economic deprivation		
		Low	Moderate	High	Low	Moderate	High	Low (most privileged)	Moderate	High (most deprived)
		0 to 0.16	>0.16 to 0.32	>0.32 to 0.74	0.0 to 0.14	>0.14 to 0.68	>0.68 to 1.0	>0.06 to 0.60	> −0.24 to 0.06	−0.69 to −0.24
Total census tracts (*N*)	376	125	126	125	125	126	125	125	126	125
					Median (interquartile range					
Proportion tree canopy cover	0.12 [0.08, 0.20]	0.17 [0.10, 0.24]	0.12 [0.07, 0.19]	0.10 [0.07, 0.14]	0.15 [0.06, 0.20]	0.12 [0.07, 0.23]	0.12 [0.10, 0.15]	0.12 [0.10, 0.15]	0.11 [0.07, 0.19]	0.16 [0.08, 0.24]
Proportion grass/shrub cover	0.18 [0.14, 0.25]	0.24 [0.12, 0.31]	0.19 [0.14, 0.24]	0.17 [0.14, 0.20]	0.18 [0.10, 0.29]	0.19 [0.14, 0.24]	0.18 [0.14, 0.23]	0.18 [0.15, 0.22]	0.19 [0.15, 0.25]	0.20 [0.10, 0.30]
Proportion adults reporting park access	0.75 [0.69, 0.81]	0.81 [0.75, 0.87]	0.75 [0.70, 0.81]	0.70 [0.65, 0.76]	0.81 [0.76, 0.87]	0.74 [0.67, 0.81]	0.71 [0.66, 0.76]	0.70 [0.65, 0.75]	0.73 [0.66, 0.78]	0.82 [0.78, 0.88]
Greenness (NDVI)	0.43 [0.35, 0.52]	0.49 [0.34, 0.61]	0.42 [0.35, 0.50]	0.41 [0.36, 0.45]	0.39 [0.31, 0.57]	0.41 [0.35, 0.51]	0.44 [0.40, 0.49]	0.43 [0.39, 0.48]	0.41 [0.35, 0.50]	0.45 [0.31, 0.61]
Population density (population/km^2)	6811.31 [4366.21, 9999.50]	4727.18 [2965.16, 8791.17]	7242.87 [5347.05, 10054.51]	7947.47 [5864.77, 10293.93]	5737.78 [3015.95, 11447.30]	7311.06 [4312.97, 9860.92]	7244.39 [5761.73, 9452.72]	7162.17 [5761.73, 9370.74]	7552.17 [5021.83, 10176.29]	4863.71 [2839.33, 10854.75]
Proportion living in poverty	0.25 [0.13, 0.37]									
Proportion non-Hispanic Black	0.30 [0.10, 0.80]									
Index of concentration at the extremes (ICE)	−0.08 [−0.33, 0.15]									

Table 2 Relative index of inequality (RII) in all-cause and cardiovascular mortality rates by census tract-level sociodemographic composition measures[1]

Composition measures	Relative index of inequality (95% CI)	
	All-cause mortality	Cardiovascular Disease mortality
Racialized economic deprivation	2.91 (2.67–3.18)	2.86 (2.58–3.17)
Proportion poverty	2.22 (2.02–2.44)	2.18 (1.95–2.43)
Proportion NH Black	1.71 (1.62–1.81)	1.70 (1.60–1.81)

[1]The relative index of inequality (RII) was estimated from a negative binomial model of age-, sex-, and tract-specific counts of all-cause or cardiovascular disease (CVD) deaths, adjusted for age and sex, by sociodemographic composition measure. Since sociodemographic composition measures are rescaled to range from 0 to 1, the RII is interpreted as the linearized mortality rate ratio between census tracts at the top vs. bottom of each composition measure. For example, areas with the highest levels of poverty have 2.22 times the all-cause mortality rate of areas at the lowest levels of poverty



[1] The relative index of inequality (RII) was estimated from a negative binomial model of age-, sex-, and census-tract specific counts of all-cause or cardiovascular disease (CVD) deaths, adjusted for age and sex categories, with the composition and green space measures and their interaction included as covariates. Since sociodemographic composition measures are rescaled to range from 0 to 1, the RII is interpreted as the linearized mortality rate ratio between census tracts at the top vs bottom of each composition measure.

[2]Low, moderate, and high categories are based on tertiles of the distribution of the greenspace variables, and coded as follows: NDVI, Low= 0.16 to 0.38, Moderate= > 0.38 to 0.49, High= > 0.49 to 0.88; Grass/shrub, Low=0.0196 to 0.155, >0.155 to 0.221, >0.221-0.470; Park, Low=0.453 to 0.717, Moderate= > 0.717 to 0.791, High=>0.791 to 0.949; Trees, Low= 0.0183 to 0.0956, Medium= >0.0956 to 0.160, High= >0.160 to 0.804

ICE, Index of Concentration at the Extremes; NDVI, Normalized difference vegetation index; NH Black, Non-Hispanic Black

Fig. 1 Relative index of inequality estimates comparing rates of mortality in Philadelphia, PA, census tracts with the highest vs. lowest levels of deprivation based on composition, stratified by tertile of each greenspace measure.[1,2]

most powerful associations may be in relation to the extreme measures of deprivation/marginalization.

A recently published review of papers that investigated the extent to which links between greenspace and health vary across levels of sociodemographics (i.e., papers that evaluated modification of associations between greenspace and health by categories of sociodemographics) found overwhelming evidence that greenspace was disproportionately protective against adverse health outcomes in low socioeconomic position groups; however, there was no strong evidence of variation of associations across racial/ethnic categories [5]. Few studies have quantified the extent to which greenspace modifies associations between sociodemographic composition and health/mortality outcomes (i.e., estimates of inequities), as we did here. In Latin America, greenness (measured using NDVI) was associated with weaker education-based inequities in violence-related mortality, but not with weaker inequities for other causes of death, including CVD [4]. In the UK, Mitchell and Popham found that the ratio comparing incidence rates of all-cause mortality in the most vs. the least income-deprived areas was 1.93 in the least green areas, but 1.43 in the greenest areas (ratio of the relative rates: 0.85) [30]; these results are quantitatively similar to the RRIIs that we observed for greenness and grass/shrub cover.

In our work, the strongest evidence in support of equigenesis was by grass/shrub coverage or greenness. Evidence for narrowing of inequities by perceived park access, in particular, was less substantial. The reasons that these different measures had varying associations with inequities in mortality rates are not clear. However, of all the measures, perceived park access had the least substantial variability across the neighborhoods. Also, the perceived park measure might have incorporated perceptions of non-green (paved) parks, which may have different associations with health, as compared with the other measures. Furthermore, the perceived park access variable may have, inadvertently, elucidated perceptions of access to other health promoting resources, such as healthy grocery stores [31]. This may have resulted in misclassification of the park access variable. Additional work that more fully explores the mechanisms underlying different associations with health and health equity across varied greenspace measures, including perceptions of green spaces, is needed.

To our knowledge, this is the first analysis to investigate the equigenic potential of greenspace for racial- or racialized economic deprivation-based inequities. We hypothesized that variation in perceptions, experiences, utilization, or quality of green spaces across neighborhood demographics would have implications for health equity promotion. Overall, we observed similar trends in association across all sociodemographic composition measures; however, the strongest equigenic trends were for ICE-based inequities. Overall, there were more substantial mortality inequities quantified using the ICE, as compared to the other sociodemographic composition measures. This is consistent with other population health research that has compared the ICE statistic with poverty composition measures [32]. The ICE measure represents the entangled constructs of poverty and race in the USA [21] and also the most extreme levels of deprivation. Thus, the most deprived populations may have the greatest to gain from green spaces.

Strengths of this work include the use of four distinct measures of greenspace, one of which was a survey-based measure of perceived park/open space access, and tree canopy and grass/shrub variables were derived from state of the art, high resolution, LiDAR-based land cover assessment data. Another strength is the use of a RRII estimate to derive a quantitative estimate of the magnitude of differences of associations across categories of the modifier. We also acknowledge several limitations. First, this Philadelphia-based study had a relatively small sample size (376 census tracts), and results may not be generalizable to other areas. The perceived park access measure did not account for differences in type or presence of vegetation, or in cleanliness, presence of graffiti, or other amenities, which may differ across categories of neighborhood sociodemographics. For example, a survey of park utilization across four metropolitan areas, including Philadelphia, found that, compared to low-poverty areas, parks in high poverty areas had more graffiti and litter on surrounding streets and also were close to poorer condition buildings [13]. Similarly, the tree canopy and grass/shrub cover measures we used did not distinguish quality or species of plant, which could have implications for health benefits. In addition, land cover assessment data were not available across all years. As a result, we used linear interpolation to derive a measure for year 2013, which was the median year across the study years. We acknowledge that this may have resulted in some misclassification of grass/shrub and tree canopy coverage. Additionally, this study relied on vital statistics data; as a result, it is possible that cardiovascular deaths were misclassified and/or under-represented. Furthermore, the objective greenspace measures that we used do not indicate whether the areas were publicly available or not. Finally, this study was ecologic in design. Thus, the results from this work cannot be used to make individual-level inferences. Nevertheless, we believe that the ecologic study design is important within the context of considering the impacts of population-level interventions on health equity, characterized at a neighborhood-level.

Conclusion

Some suggest that the rapid rate at which the world is urbanizing will magnify health inequities [33]. If designed and implemented thoughtfully and appropriately, urban interventions may be leveraged to promote equity. Our results support the hypothesis that greenspace interventions may be associated with more narrow inequities in neighborhood-level mortality rates—especially inequities that are based on the highest levels of deprivation, and which may be rooted in historical and present-day systems of racism, such as racialized residential segregation and disinvestment [34]. Trends were more substantial for overall greenness and grass/shrub, suggesting that different greenspace types may have different associations with health equity. These results are based on an ecologic analysis and focused on a single city. Thus, we emphasize the need to replicate them in other settings and using different study designs. In addition, in considering greening programs as an intervention, it is important to consider the potential for longer-term adverse implications for health equity at a neighborhood level, for example, through gentrification processes that may lead to feelings of social or cultural exclusion [35]. Overall, these results suggest the potential value but also the associated complexities associated with designing interventions to promote health equity in urban settings.

Acknowledgements This work was supported by the American Heart Association—Award # 00015611 (LHS). Usama Bilal was supported by the Office of the Director of the National Institutes of Health Award # DP5OD26429 (UB). Janelle Edwards was supported through a doctoral fellowship from the Urban Health Collaborative at the Dornsife School of Public Health at Drexel University (JE).

Author Contribution Leah Schinasi conceived the research question and led the statistical analyses, analysis interpretation, and manuscript writing. Usama Bilal contributed to statistical analysis development, data interpretation and presentation, and manuscript writing. Jane Clougherty, Anneclaire De Roos, Michelle Kondo, and Janelle Edwards contributed to data interpretation and manuscript writing. All authors reviewed and approved the final version of this manuscript.

Declarations

Disclaimer The Pennsylvania Department of Health specifically disclaims responsibility for any analyses, interpretations, or conclusions. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

References

1. World Health Organization. *Urban green spaces and health.* 2016. https://apps.who.int/iris/bitstream/handle/10665/345751/WHO-EURO-2016-3352-43111-60341-eng.pdf?sequence=3&isAllowed=yhttps://apps.who.int/iris/bitstream/handle/10665/345751/WHO-EURO-2016-3352-43111-60341-eng.pdf?sequence=3&isAllowed=y. Accessed 20 May 2022.
2. Markevych I, Schoierer J, Hartig T, Chudnovsky A, Hystad P, Dzhambov AM, de Vries S, Triguero-Mas M, Brauer M, Nieuwenhuijsen MJ, Lupp G, Richardson EA, Astell-Burt T, Dimitrova D, Feng X, Sadeh M, Standl M, Heinrich J, Fuertes E. Exploring pathways linking greenspace to health: theoretical and methodological guidance. *Environ Res.* 2017;158:301–17. https://doi.org/10.1016/j.envres.2017.06.028.
3. Mitchell RJ, Richardson EA, Shortt NK, Pearce JR. Neighborhood environments and socioeconomic inequalities in mental well-being. *Am J Prev Med.* 2015;49(1):80–4. https://doi.org/10.1016/j.amepre.2015.01.017.
4. Moran MR, Bilal U, Dronova I, Ju Y, Gouveia N, Caiaffa WT, Friche AAL, Moore K, Miranda JJ, Rodriguez DA. The equigenic effect of greenness on the association between education with life expectancy and mortality in 28 large Latin American cities. *Health Place.* 2021;72:102703. https://doi.org/10.1016/j.healthplace.2021.102703.
5. Rigolon A, Browning M, McAnirlin O, Yoon HV. Green Space and health equity: a systematic review on the potential of green space to reduce health disparities. *Int J Environ Res Public Health.* 2021;18(5):2563. https://doi.org/10.3390/ijerph18052563.
6. Mitchell R. What is equigenesis and how might it help narrow health inequalities? 2013. https://cresh.org.uk/2013/11/08/what-is-equigenesis-and-how-might-it-help-narrow-health-inequalities/
7. Gronlund CJ. Racial and socioeconomic disparities in heat-related health effects and their mechanisms: a review. *Curr Epidemiol Rep.* 2014;1(3):165–73. https://doi.org/10.1007/s40471-014-0014-4.
8. Ferdows NB, Aranda MP, Baldwin JA, Baghban Ferdows S, Ahluwalia JS, Kumar A. Assessment of racial disparities in mortality rates among older adults living in US rural vs urban counties from 1968 to 2016. *JAMA*

Netw Open. 2020;3(8):e2012241. https://doi.org/10.1001/jamanetworkopen.2020.12241.
9. Bailey ZD, Krieger N, Agenor M, Graves J, Linos N, Bassett MT. Structural racism and health inequities in the USA: evidence and interventions. *Lancet.* 2017;389(10077):1453–63. https://doi.org/10.1016/S0140-6736(17)30569-X.
10. Jones CP. Levels of racism: a theoretic framework and a gardener's tale. *Am J Public Health.* 2000;90(8):1212–5. https://doi.org/10.2105/ajph.90.8.1212.
11. Nardone A, Rudolph KE, Morello-Frosch R, Casey JA. Redlines and greenspace: the relationship between historical redlining and 2010 greenspace across the United States. *Environ Health Perspect.* 2021;129(1):17006. https://doi.org/10.1289/EHP7495.
12. Casey JA, James P, Cushing L, Jesdale BM, Morello-Frosch R. Race, Ethnicity, income concentration and 10-year change in urban greenness in the United States. *Int J Environ Res Public Health.* 2017;14(12). https://doi.org/10.3390/ijerph14121546.
13. Cohen DA, Lapham S, Evenson KR, Williamson S, Golinelli D, Ward P, Hillier A, McKenzie TL. Use of neighbourhood parks: does socio-economic status matter? A four-city study. *Public Health.* 2013;127(4):325–32. https://doi.org/10.1016/j.puhe.2013.01.003.
14. Hoover FA, Lim TC. Examining privilege and power in US urban parks and open space during the double crises of antiblack racism and COVID-19. *Socio-ecol Pract Res.* 2021;3(1):55–70. https://doi.org/10.1007/s42532-020-00070-3.
15. Schinasi LH, Kanungo C, Christman Z, Barber S, Tabb L, Headen I. Associations between historical redlining and present-day heat vulnerability housing and land cover characteristics in Philadelphia PA. *J Urban Health.* 2022;99(1):134–45. https://doi.org/10.1007/s11524-021-00602-6.
16. Pearsall H, Christman Z. Tree-lined lanes or vacant lots? Evaluating non-stationarity between urban greenness and socio-economic conditions in Philadelphia, Pennsylvania USA at multiple scales. *Appl Geogr.* 2012;35(1-2):257–64.
17. Knobel P, Kondo M, Maneja R, Zhao Y, Dadvand P, Schinasi LH. Associations of objective and perceived greenness measures with cardiovascular risk factors in Philadelphia, PA: a spatial analysis. *Environ Res.* 2021;197:110990. https://doi.org/10.1016/j.envres.2021.110990.
18. Diez Roux AV. Investigating neighborhood and area effects on health. *Am J Public Health.* 2001;91(11):1783–9.
19. Krieger N, Rehkopf DH, Chen JT, Waterman PD, Marcelli E, Kennedy M. The fall and rise of US inequities in premature mortality: 1960–2002. *PLoS Med.* 2008;5(2):e46.
20. US Census Bureau. *2011-2015 American Community Survey 5-year estimates*. 2015. https://www.census.gov/programs-surveys/acs/technical-documentation/table-and-geographychanges/2015/5-year.html. Accessed 3 Aug 2023.
21. Krieger N, Waterman PD, Spasojevic J, Li W, Maduro G, Van Wye G. Public health monitoring of privilege and deprivation with the index of concentration at the extremes. *Am J Public Health.* 2016;106(2):256–63. https://doi.org/10.2105/AJPH.2015.302955.
22. O'Neil-Dunne J. *A report on the city of Philadelphia's existing and possible tree canopy*. 2011. https://www.phila.gov/media/20200210164446/Urban-Tree-Canopy-Report-03-18-11.pdf. Accessed 3 Aug 2023.
23. O'Neil-Dunne J. *Philadelphia Tree Canopy Assessment*. 2019. https://treephilly.org/wpcontent/uploads/2019/12/Tree-Canopy-Assessment-Report-Philadelphia-2018.pdf. Accessed 3 Aug 2023.
24. Ramankutty N, Foley JA. Estimating historical changes in global land cover: croplands from 1700 to 1992. *Global Biogeochem Cycles.* 1999;13(4):997–1027.
25. Quick H, Terloyeva D, Wu YX, Moore K, Roux AVD. Trends in tract-level prevalence of obesity in Philadelphia by race-ethnicity, space, and time. *Epidemiology.* 2020;31(1):15–21. https://doi.org/10.1097/ede.0000000000001118.
26. Chander G, Markham BL, Helder DL. Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors. *Remote Sens Environ.* 2009;113(5):893–903. https://doi.org/10.1016/j.rse.2009.01.007.
27. Hijmans RJ, van Etten J. raster: geographic analysis and modeling with raster data. *R Package Version.* 2012:2.0–12.
28. Moreno-Betancur M, Latouche A, Menvielle G, Kunst AE, Rey G. Relative index of inequality and slope index of inequality: a structured regression framework for estimation. *Epidemiology.* 2015;26(4):518–27. https://doi.org/10.1097/ede.0000000000000311.
29. Altman DG, Bland JM. Interaction revisited: the difference between two estimates. *BMJ.* 2003;326(7382):219.
30. Mitchell R, Popham F. Effect of exposure to natural environment on health inequalities: an observational population study. *Lancet.* 2008;372(9650):1655–60. https://doi.org/10.1016/S0140-6736(08)61689-X.
31. Rodriguez-Loureiro L, Casas L, Bauwelinck M, Lefebvre W, Vanpoucke C, Gadeyne S. Long-term exposure to objective and perceived residential greenness and diabetes mortality: a census-based cohort study. *Sci Total Environ.* 2022;821:153445.
32. Krieger N, Waterman PD, Batra N, Murphy JS, Dooley DP, Shah SN. Measures of local segregation for monitoring health inequities by local health departments. *Am J Public Health.* 2017;107(6):903–6. https://doi.org/10.2105/ajph.2017.303713.
33. WHO. *Hidden cities: unmasking and overcoming health inequities in urban settings*. 2010. https://www.who.int/publications/i/item/9789241548038. Accessed 3 Aug 2023.
34. Bailey ZD, Feldman JM, Bassett MT. How structural racism works—racist policies as a root cause of US racial health inequities. *N Engl J Med*. 2021;384(8):768–773. https://doi.org/10.1056/NEJMms2025396.
35. Cole HVS, Garcia Lamarca M, Connolly JJT, Anguelovski I. Are green cities healthy and equitable? Unpacking the relationship between health, green space and gentrification. *J Epidemiol Community Health.* 2017;71(11):1118–21. https://doi.org/10.1136/jech-2017-209201.