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Gender and violent crime modify associations between greenspace and cardiovascular disease mortality in Philadelphia, PA

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A B S T R A C T

Few studies have explored variability of associations between greenspace and cardiovascular (CVD) mortality according to demographic or neighborhood contextual factors. We estimated overall and sex-stratified associations between greenspace and CVD mortality rates in Philadelphia, PA, and quantified effect modification of the sex-stratified associations by neighborhood violent crime rates. Sex- and age-stratified census tract CVD mortality rates (years 2008–2015) were linked with proportion tree canopy cover, grass/shrub cover, and total vegetation cover, and proportion of adult residents reporting access to a park. We used multivariable negative binomial models to estimate overall and sex-stratified associations between neighborhood greenspace and CVD mortality rates, and quantified effect modification by tract-level rates of violent crime. Higher proportion tree canopy cover and higher proportion adults reporting access to parks were associated with modestly lower rates of CVD mortality, with more pronounced estimates in males than females. In tracts with higher rates of crime, higher tree canopy coverage and perceived park access were associated with lower CVD mortality rates. We did not observe strong evidence of sex-based differences in interaction between neighborhood crime rates and greenspace. Results from this study reveal variability of associations between greenspace and CVD mortality rates according to sex categories, and according to neighborhood social environments. There is a need for further research exploring the extent to which differences in perceived safety explain gender-based differences in associations between greenspace and cardiovascular outcomes.

1. Introduction

Research from across the globe suggests that greenspace may protect against cardiovascular disease (CVD), the leading cause of death in the U.S. before the COVID-19 pandemic (Gascon et al., 2016; Yuan et al., 2021). Greenspace may protect against CVD through a variety of hypothesized pathways, including psychological restoration (e.g., stress reduction), harm reduction (e.g., buffering noise, air pollution, heat), and capacity building (e.g., enhancing social cohesion or promoting physical activity) (Markevych et al., 2017). Associations between greenspace and health have been shown to vary according to population demographics, including gender (Stafford et al., 2005; Kondo et al., 2021). For example, some studies suggest that greenspace has stronger protective associations with CVD mortality in men (Richardson et al., 2010).

Consistent with others, we distinguish between the terms sex and gender; we characterize gender as a socially determined construct, and sex as a biologic one. Herein, we focus on gender as the construct relevant to explaining heterogeneity in associations between greenspace and CVD mortality outcomes. The reason for this is that gender is socialized, it is impacted by culture and societal norms, and it has implications for differential behavioral and time-use patterns seen across individuals (Clougherty, 2010). For example, gender-based differences in associations between greenspace and CVD mortality outcomes may be explained, at least in part, by differences in greenspace utilization patterns. Women have been shown to have lower frequency and duration of neighborhood park utilization compared to men (Cohen et al., 2016; Derose et al., 2018); this could be a critical mediating factor in the pathway between greenspace and cardiovascular health protection (Wan et al., 2022). One explanation for gender-based differences in utilization may be variation in perceptions of safety associated with greenspace visitation. It is well accepted that women have greater perceived risk compared to men (Gustafson, 1998) and that risk perception has a powerful impact on health behavior (Brewer et al., 2007). For example, studies have demonstrated that greater perceived safety is associated with more physical activity engagement (e.g.,

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walking outdoors) (Foster et al., 2004; Suminski et al., 2005).

It is well documented that women feel a greater fear of crime as compared to men, and that this fear shapes their interaction with, and use of urban spaces, including parks and green spaces (Gordon et al., 1980). In Los Angeles, CA, higher frequency of park utilization in men versus women was partially explained by greater perceived crime among women (Derose et al., 2019; Sreetheran et al., 2014). Objective measures of crime may overlap, but not perfectly correlate, with individual level fears and concerns, which are also a product of social, cultural, and psychological factors (Vitelli et al., 1993). While studies have shown that green spaces are associated with lower rates of objectively measured neighborhood crime rates (Shepley et al., 2019), few studies have explored the extent to which objectively measured crime modifies associations between greenspace and CVD mortality, overall, and according to gender categories. Such information is critical for elucidating the populations and neighborhoods that green spaces benefit, and for unpacking reasons that green spaces may not always promote health (James et al., 2016).

Here, we report results from an analysis of associations between neighborhood greenspace and overall and gender-specific CVD mortality rates, and heterogeneity of these associations according to neighborhood rates of violent crime. We conducted this analysis in Philadelphia, PA, one of the largest cities in the U.S. In year 2009, the city launched its "Greenworks" sustainability plan, which included a goal of achieving 30 percent tree coverage per neighborhood by year 2025 (Kondo et al., 2020). Philadelphia has high variability in greenspace coverage (Schinasi et al., 2019) and has some of the highest rates of crime in the U.S. (Everybody is armed, 2022; Shootings in Philadelphia, 2022).

In addition to assessing heterogeneity of associations according to categories of gender and neighborhood crime rates, an important contribution of this study is that we estimate associations with different greenspace types. To date, most studies of associations between greenspace and mortality outcomes have estimated associations using aggregate measures of greenness, such as the normalized difference vegetation index (NDVI). This measure does not reveal if the direction or magnitude of associations between greenspace and mortality outcomes varies according to type, nor does it shed light on whether perceptions of greenspace impact its health benefits (Rojas-Rueda et al., 2019; Nieuwenhuijsen et al., 2017). We hypothesized that the protective association between greenspace and CVD mortality would be stronger among men, and in neighborhoods with lower rates of crime. Further, we hypothesized that crime rates would have less of a modifying effect of the association between greenspace and crime rates in men than women. Finally, we hypothesized stronger associations for perceived park access, which may confer more park utilization, compared to other greenspace indicators. A conceptual diagram showing hypothesized relationships between gender identity, objectively measured crime rates, perceived safety, greenspace, and cardiovascular mortality is shown in Supplementary Fig. 1.

2. Methods

We conducted an ecologic analysis of associations of different types of neighborhood-level greenspace (proportion total vegetation cover, proportion tree canopy cover, proportion grass/shrub cover, and proportion of residents reporting access to parks) with rates of cardiovascular (CVD) mortality. The period for the analysis was 2008–2015 and the study setting was Philadelphia, PA. The unit of analysis was the U.S. Census tract, which we defined using 2010 boundaries. U.S. Census tracts are administrative units that are commonly used in population health research to approximate neighborhoods (US Census Bureau, 2022). In Philadelphia, tracts are densely populated (average population density based on 2011–2015 ACS data: 7390 people/km^2). There are 384 census tracts in Philadelphia; we excluded eight non-residential census tracts and two additional ones that did not have crime data, leaving 374 in the analysis.

2.1. Data

Mortality data came from the Bureau of Health Statistics and Registries of the Pennsylvania Department of Health, Harrisburg, Pennsylvania. We calculated census-tract level sex (female vs male) and age (<18, 18–44, 45–64, 65+) stratified counts of CVD (ICD-10 codes I00-I99) mortality in years 2008–2015. We aimed to capture differences according to gender identity, which is a social construct (Krieger, 2003). However, the mortality data contained only binary sex categories (female/male) and did not indicate if people identified as non-binary or transgender. Therefore, from this point forward, we use the term "sex" instead of "gender" to describe the methods and results, even though we hypothesize that gender identity is the relevant construct with respect to shaping experiences, perceptions, and behaviors in greenspace. We linked the mortality data with the following tract level measures from the American Community Survey (five-year average estimates, years 2011–2015): sex- and age-stratified population counts for creation of sex-specific tract-level CVD mortality rates, as well as proportion living in poverty, proportion identifying as non-Hispanic Black, and population density (people/km^2) (US Census Bureau, 2022). We also linked in the index of concentration at the extremes (ICE) measure of racialized economic deprivation, which was derived from 2011 to 2015 ACS tract-level median household income and proportion non-Hispanic Black data. The ICE is a quantitative measure that compares concentrations of low-income Black residents with concentrations of high-income White ones. The measure ranges from −1 (indicating the most deprived tracts) to 1 (indicating the least deprived tracts). The ICE statistic was calculated using methods used by Krieger et al. (2016), using the following formula: $(A_i - D_i)/T_i$, where A_i is the number of non-Hispanic White residents in a census tract i, D_i is the number of non-Hispanic Blacks, and T_i is the total number of residents.

We used the following census-tract level measures of greenspace: proportion tree canopy cover, proportion grass/shrub cover, proportion total vegetation cover, and proportion of adult residents reporting access to a park or open space in the year 2013. Tree canopy, grass/shrub, and total vegetation cover estimates were calculated from high resolution (30.5 cm × 30.5 cm, or 1 ft. by 1 ft. pixels) orthophotography and Light Detection and Ranging (LiDAR) based land cover assessment data, collected for two land cover assessments of Philadelphia, conducted in years 2008 and 2018 (O'Neil-Dunne, 2011). The measures were calculated by dividing the land area covered by tree canopy or grass/shrub cover by the total land area in each tract. We calculated total vegetation cover by summing the total tree canopy cover and grass/shrub cover variables. We used linear interpolation to derive estimates for the year 2013, which is the midpoint between the years of the two land cover assessments (Ramankutty et al., 1999). In exploratory analyses, we observed little change in percent tree canopy, grass/shrub, or total vegetation coverage from year 2008–2018 (Supplementary Fig. 2). Tract level measures of proportion of adult residents reporting access to a park or open space were estimated using responses to the following question in the 2013 Southeastern Pennsylvania Household Health Survey (SEPHHS): "Is there a park or other outdoor space in your neighborhood that you are comfortable visiting during the day?" The SEPHHS was a survey of a representative sample of the non-institutionalized adult population living in Southeastern Pennsylvania, identified using random digit dialing, conducted biennially from 2000 to 2014/2015. Survey participants were asked questions about their health, behavior, and neighborhood environments. The SEPHHS dataset also provided the residential census tract of heat respondent at the time that the survey was conducted. Tract level estimates, representing proportions of residents with access to parks or open space, were calculated using Bayesian hierarchical models that account for spatial and temporal dependencies. Details on the methods used to derive these tract level estimates are reported elsewhere (Quick et al., 2020).

Annual census-tract level rates of violent crime for year 2013 (per km^2) were calculated using Philadelphia Police Department's crime incident data (accessed from the City of Philadelphia's Open data repository) (OpenDataPhilly, 2024). In accordance with the Federal Bureau of Investigation's uniform crime reporting categories, violent crimes were identified as incidents of murder/homicide, aggravated assault, robbery, or rape (US Department of Justice, 2004).

2.2. Analysis

We conducted all analyses for the entire population and stratified by sex categories (male/female). We estimated associations using negative binomial models with an offset for log-transformed total population counts (age-stratified, and, for sex-stratified analyses, age and sex-stratified) in each census tract. We assumed a negative binomial, rather than a Poisson distribution, based on evidence of overdispersion in the data.

We ran models with each greenspace variable as the primary explanatory variable, individually. We coded each greenspace measure as a three-level categorical term, with categories based on tertiles of the distribution across the Philadelphia census tracts (tertile 1 = least green, tertile 2 = moderately green, 3 = most green, values given in Table 1). We selected this parametrization because of evidence in preliminary analyses of non-linear associations with CVD mortality rates. We created the three-level categories based on tertiles of the distribution across the tracts in order to represent different levels of greenspace (low to high), while also allowing sufficient numbers of tracts (the primary unit of analysis) within each category. The categorical parametrization also allowed for simple presentation and interpretation of estimates, particularly in models that included interaction terms with crime rates (described in detail below). We adjusted the models for the following: categorical age (<18, 18–44, 45–64, 65+ years), sex (male vs. female) in non-sex stratified models, population density per km^2, and the ICE from 2011 to 2015. The population density and ICE variables were coded as tertile-based categorical terms, also due to evidence of non-linear associations with CVD mortality rates; we selected tertiles to ensure sufficient statistical power within strata. While we used tract level measures of proportions of residents living in poverty and proportion identifying as non-Hispanic Black in descriptive statistics, the ICE measure of racialized economic deprivation was used as the adjustment variable, in models. The ICE measure quantifies the extent of privilege or disadvantage within a census tract (Krieger et al., 2016). We included the ICE measure to capture the cumulative burden of being both racially and socioeconomically marginalized. Furthermore, the inclusion of the ICE measure, rather than race and income/poverty, prevented collinearity between race/ethnicity and poverty/income measures. We selected the full covariate set for inclusion in models set by developing a direct acyclic diagram (DAG) (Supplementary Fig. 3) (Krieger et al., 2016).

We assessed effect modification of associations between greenspace and CVD mortality rates by crime rates (counts per km^2) by including interaction terms between each greenspace measure and tract level crime rates. We modeled crime rates as a three level tertile based categorical term. We selected this parameterization to represent the distribution of crime rates across Philadelphia, while allowing sufficient statistical power. To assess statistical evidence of modification, we conducted likelihood ratio tests (LRT), comparing nested models with and without interaction terms. All models with interaction terms contained the full covariate adjustment set. We report rate ratio (RR) estimates of association, comparing CVD mortality rates in census tracts belonging to the second and third tertiles of greenspace measure with rates in first-tertile census tracts as the referent.

As a sensitivity analysis, to further relax assumptions about the shape of the dose-response relationship between the greenspace measures and CVD mortality rates, we reran the primary and sex-stratified models with greenspace parameterized using natural cubic B splines with three degrees of freedom. Also, to account for potential misclassification of greenspace exposures resulting from longitudinal changes in land cover, over time, we reran models using greenspace measures from 2008 – the first year for which land cover data are available. All the statistical analyses were conducted in R (version 4.1.2) using the 'pscl' package.

Table 1
Distribution of key variables in the 374 Philadelphia, PA census tracts included in the analysis (low: [0th percentile to ≤ 33rd percentile; medium: 33rd percentile to ≤ 67th percentile; high: >67th percentile].

Variable		All (N = 374)
Proportion tree canopy cover		
Tertiles	Low	(0.02,0.10)
	Medium	(0.10,0.16)
	High	(0.16,0.77)
Percentiles (25th, 75th)		0.08, 0.20
Mean(sd)		0.15(0.11)
Median(min,max)		0.12(0.02,0.77)
Proportion Grass/shrub cover		
Tertiles	Low	(0.02,0.15)
	Medium	(0.15,0.22)
	High	(0.22,0.47)
Percentiles (25th, 75th)		0.14, 0.26
Mean(sd)		0.20(0.08)
Median(min,max)		0.18(0.02,0.47)
Proportion Total vegetation cover		
Tertiles	Low	(0.05,0.26)
	Medium	(0.26,0.39)
	High	(0.39,0.91)
Percentiles (25th, 75th)		0.23, 0.44
Mean(sd)		0.35(0.16)
Median(min,max)		0.31(0.05,0.91)
Proportion of adult residents reporting park or open space access		
Tertiles	Low	(0.45,0.71)
	Medium	(0.71,0.79)
	High	(0.79,0.95)
Percentiles (25th, 75th)		0.69, 0.81
Mean(sd)		0.75(0.09)
Median (min,max)		0.75(0.45,0.95)
Proportion of Non-Hispanic Black		
Tertiles	Low	(0.00,0.14)
	Medium	(0.14,0.69)
	High	(0.69,1.00)
Percentiles (25th, 75th)		0.10, 0.80
Mean(sd)		0.42(0.35)
median(min,max)		0.30(0.00,1.00)
Proportion living in poverty		
Tertiles	Low	(0.00,0.16)
	Medium	(0.16,0.33)
	High	(0.33,0.74)
Percentiles (25th, 75th)		0.13, 0.37
Mean(sd)		0.26(0.16)
Median(min,max)		0.25(0.00,0.74)
Index of Concentration at the Extremes		
Tertiles	Low	(-0.69,-0.25)
	Medium	(-0.25,0.06)
	High	(0.06,0.60)
Percentiles (25th, 75th)		−0.33, 0.15
Mean(sd)		−0.09(0.28)
Median(min,max)		−0.09(-0.69,0.60)
Population density (population/km^2)		
Tertiles	Low	(92,5375)
	Medium	(5375,8819)
	High	(8819,25754)
Percentiles (25th, 75th)		4405, 10027
Mean(sd)		7584(4385)
Median(min,max)		6867(92,25754)
Violent crime rates (count per km^2)		
Tertiles	Low	(2108)
	Medium	(108,249)
	High	(249,938)
Percentiles (25th, 75th)		72, 290
Mean(sd)		200(153)
Median(min,max)		177(2938)

3. Results

Amount of greenspace varied across the 374 residential census tracts (Table 1). Mean proportions of tree canopy, grass/shrub, and total vegetation cover were 0.15 (range: 0.02 to 0.77), 0.20 (range: 0.02 to 0.47), and 0.35 (range: 0.05 to 0.91), respectively. Mean percentage of adult residents reporting access to parks was 75% (range: 45%–95 %). In addition, the tracts varied with respect to the percentage non-Hispanic Black (median = 30%, range: 0–100%) and poverty composition (median = 25%, range: 0–74%). Mean population density was 7584 people per km^2, ranging from 92 to 25,754. Mean ICE index across census tracts was −0.09, ranging from −0.69 to 0.60. Proportion tree canopy, grass/shrub and total vegetation cover were lower in census tracts with higher crime rates. Tracts with higher crime rates had higher proportions of residents identifying as non-Hispanic Black and living in poverty (Supplementary Table 1). Total vegetation cover was highly correlated with tree canopy (r = 0.88) and grass/shrub cover (r = 0.80), while tree canopy and grass/shrub cover were only moderately correlated (r = 0.43), and residents reporting access to a park or open space was modestly correlated with tree canopy (r = 0.33) and total vegetation cover (r = 0.22, Supplementary Fig. 4). Tract-level sociodemographic composition measures were modestly correlated with each other and with the greenspace measures.

3.1. *Overall associations*

After adjusting for age, sex, population density, and the ICE, rates of CVD mortality were lower in association with the highest level of tree canopy cover [3rd tertile RR = 0.84 (95% CI: 0.79–0.90)]. In addition, the overall estimates for total vegetation were in the protective direction [3rd tertile RR = 0.90 (95% CI: 0.84–0.96)]. We observed null overall associations with grass/shrub, as well as with proportion of adult residents reporting access to parks or open space (Table 2).

3.2. *Sex-stratified associations*

Among males, CVD mortality rates were lower in association with the highest levels of all the greenspace measures, and especially tree canopy cover ([3rd tertile RR: 0.81 (0.76–0.88)] and total vegetation [3rd tertile RR: 0.86 (0.79–0.93)]; these estimates were slightly stronger in magnitude (i.e., further from the null) than the estimates of association in the total population. Associations with park access [3rd tertile RR: 0.92, 95% CI: 0.84–1.00] and proportion of grass/shrub cover [3rd tertile RR: 0.93, 95% CI: 0.86–1.02] were in the protective direction, although they did not exhibit statistical significance (Table 2). Among females, estimates of association with proportion tree canopy cover [3rd tertile RR: 0.88 (0.80–0.96)] were in the protective direction, although they were closer to the null as compared to associations among males. Associations with the other greenspace measures were close to the null.

3.3. *Effect modification by crime rates*

Protective associations with park access were restricted to tracts in which rates of crime were highest, and there was strong statistical evidence of modification by crime for this association (p for LRT <0.01). Specifically, there were incrementally lower rates of CVD mortality in association with higher amounts of proportion adults reporting park access, moving from low to higher crime rates [3rd tertile RR in tracts with low crime: 1.18 (1.04–1.34); moderate crime: 1.06 (0.95–1.18); high crime: 0.83 (0.73–0.94)]. Also, in tracts with the highest rates of crime, there were lower rates of CVD mortality in association with high proportion tree canopy cover (3rd tertile RR in tracts with the lowest, moderate, and highest rates of crime, respectively: 0.91, 95% CI: 0.81–1.02; 0.87, 95% CI: 0.79–0.96; 0.77, 95% CI: 0.63–0.94; p for LRT: 0.12). Higher proportion total vegetation cover was associated higher rates of CVD mortality in tracts with the highest rates of crime [3rd tertile RR in tracts with high crime: 1.19 (0.95, 1.49); p for LRT: 0.12]. However, associations with total vegetation cover were close to the null in tracts with the lowest rates of crime. We did not observe evidence of effect modification of associations with grass/shrub cover (Fig. 1; Supplementary Table 2).

Table 2
Rate ratio (95% CI) estimates of association between census tract-level greenspace measures and rates of cardiovascular (CVD) mortality, comparing the 2nd (33rd to ≤ 67th percentile) and 3rd tertiles (>67th percentile) of the distribution of greenspace with the first tertile (referent, ≤33rd percentile), for the entire population, and stratified by sex (male vs. female).[a] and[b].

Population	Exposure	Tertile	CVD mortality	RR	95% CI
All	Tree	T1	10968	Ref	
		T2	12590	0.94	(0.89–0.99)
		T3	11252	0.84	(0.79–0.90)
	Grass/Shrub	T1	10017	Ref	
		T2	11084	0.98	(0.92–1.04)
		T3	13709	0.98	(0.92–1.05)
	Total vegetation	T1	10460	Ref	
		T2	11169	0.87	(0.82–0.93)
		T3	13181	0.90	(0.84–0.96)
	Park	T1	11681	Ref	
		T2	11968	0.97	(0.92–1.03)
		T3	11161	0.97	(0.91–1.04)
Male	Tree	T1	5478	Ref	
		T2	5926	0.92	(0.86–0.99)
		T3	5314	0.81	(0.76–0.88)
	Grass/Shrub	T1	5006	Ref	
		T2	5345	0.94	(0.87–1.01)
		T3	6367	0.93	(0.86–1.02)
	Total vegetation	T1	5258	Ref	
		T2	5316	0.85	(0.79–0.92)
		T3	6144	0.86	(0.79–0.93)
	Park	T1	5839	Ref	
		T2	5759	0.95	(0.89–1.02)
		T3	5120	0.92	(0.84–1.00)
Female	Tree	T1	5490	Ref	
		T2	6664	0.96	(0.88–1.04)
		T3	5938	0.88	(0.80–0.96)
	Grass/Shrub	T1	5011	Ref	
		T2	5739	1.02	(0.93–1.11)
		T3	7342	1.04	(0.94–1.15)
	Total vegetation	T1	5202	Ref	
		T2	5853	0.89	(0.81–0.98)
		T3	7037	0.94	(0.85–1.05)
	Park	T1	5842	Ref	
		T2	6209	0.99	(0.91–1.08)
		T3	6041	1.05	(0.95–1.16)

Abbreviations: T1: 1st tertile of greenspace exposure (referent, least green); T2: 2nd tertile of greenspace exposure; [2]T3: 3rd tertile of greenspace exposures (most green).

[a] Estimates are derived from negative binomial regression models, adjusted for age, sex, population density, and the index of concentration at the extremes (ICE) measure of racialized economic deprivation.

[b] Sex was not included as a covariate in sex-stratified models. The ICE measures was calculated using American Community Survey data on median household income and proportion non-Hispanic Black, and ranged from −1 (most deprived) to 1 (most privileged).

3.4. *Effect modification by violent crime, stratified by sex*

Overall, we observed little statistical evidence of effect modification by crime in the sex-stratified analyses, though there was evidence of modification of the associations with perceived park access (Fig. 1; Supplementary Table 2). We observed similar trends among both males and females, with higher proportion park access being associated with lower rates of CVD mortality in tracts with higher rates of crime (p for LRT of the interaction term between crime rates and proportion park

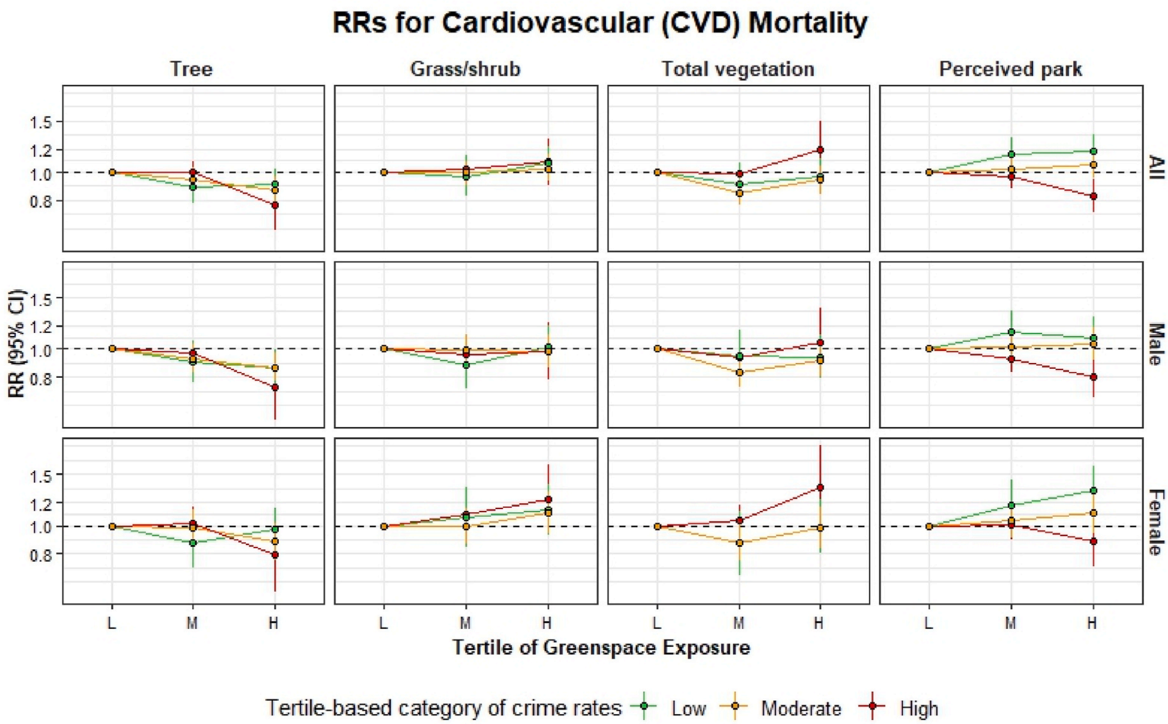

Fig. 1. Rate Ratio and 95% confidence intervals estimates of association between census-tract level greenspace measures and cardiovascular mortality rates stratified by rates of violent crime.[1] [1]Rate ratios compare the 2nd and 3rd tertiles of the greenspace measures with the lowest tertile (L: low, M: medium; H: high). Tertiles of crime rates are presented as 'low', 'moderate', and 'high' (colored green/orange/red, respectively). Crime rate stratified estimates were derived from negative binomial models containing interaction terms between the greenspace variable and the variable representing tract-level crime rates. Models were adjusted for age, sex, population density, and the index of concentration at the extremes (ICE) measure of racialized economic deprivation. Sex was not included as a covariate in sex-stratified models. Abbreviations: Tree: Proportion tree canopy cover; Grass/shrub: Proportion grass/shrub cover; Total vegetation: Proportion tree/grass/shrub; Perceived park: Proportion of adult residents reporting access to parks or open space. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

access for males and females, respectively: 0.03 and 0.07). For example, among males, neighborhoods with the highest tertile of rates of crime had lower rates of CVD mortality in association with high proportion residents reporting access to parks [RR for the comparison of the third with the first tertile of park access: 0.80 (0.68–0.94)]. By contrast, in neighborhoods with the lowest rates of crime, the association between high proportion park access and CVD mortality in males were close to the null (RR: 1.09, 95% CI: 0.93–1.28).

3.5. *Sensitivity analysis*

Results from models in which we parameterized the greenspace variables using a natural cubic spline term with 3 degrees of freedom were similar to the results from models run with greenspace modeled as a three level categorical term (Supplementary Fig. 5). Estimates of association derived from models run using 2008 measures of greenspace were similar to those obtained from those using 2013 estimates (Supplementary Tables 3 and 4).

4. Discussion

To our knowledge, this is the first analysis to explore modification of sex-specific associations between neighborhood greenspace and CVD mortality by rates of violent crime. After adjusting for neighborhood population density and racialized economic deprivation, as well as sex and age, we observed protective associations of tract-level proportion tree canopy cover and proportion of adult residents reporting access to parks or open spaces with rates of CVD mortality, especially among males. Protective associations with tree canopy cover were stronger in high crime rate neighborhoods; and those with perceived park access were restricted to high crime rate neighborhoods. Taken together, these results suggest that personal identity and neighborhood context may be important modifiers of associations between green spaces and CVD mortality.

Results suggesting sex-based differences in the associations between objectively measured greenspace and CVD mortality rates are consistent with some, but not all, previously published research (Sillman et al., 2022), though the social contexts of the settings of past research may differ from those in Philadelphia, PA - in terms of levels of crime, determinants of perceived safety, cultural preferences, gender identities, etc. Most previous published research has used objective measures of greenspace, often quantified as overall greenspace coverage or density, as opposed to distinguishing across type as we did in our analysis. Consistent with our results that suggested stronger protective associations with objectively measured tree canopy cover and total vegetation among males than females, an ecological study conducted in the United Kingdom found stronger protective associations between percent greenspace coverage and cardiovascular disease mortality among men than women (Richardson et al., 2010). Also consistent with our findings, in Canada, higher levels of residential greenness, measured using the Normalized Difference Vegetation Index (NDVI), were associated with lower risk of all-cause mortality in men vs. women (Crouse et al., 2017), and in Lithuania, greater distances of the residence from accessible green spaces were associated with higher risk of total cardiovascular disease in men, but not in women (Tamosiunas et al., 2014). Also, in a laboratory experiment that exposed participants to varying densities of tree canopy using three dimensional videos set in four mid-Western U.S. cities, moderate levels of tree density were associated with biomarkers of stress reduction in men but not women (Jiang et al., 2014). In contrast to our results, in Rome, greater leaf area index (as a measure of tree canopy) within 300 m of the residence was associated with modest protection against mortality from cardiovascular disease among females, but not in males (Orioli et al., 2019). Also in conflict with our findings, in Switzerland, residential greenspace (measured by NDVI as total greenness density) was more protective against CVD mortality among females vs. males (Vienneau et al., 2017).

Our results also suggested that higher levels of perceived park or open space access were associated with lower rates of CVD mortality among males but not females. These results are consistent with our *a priori* hypotheses, and with evidence demonstrating gender-based differences in utilization of green spaces and of perceptions of safety in parks (Gordon et al., 1980; Derose et al., 2019; Sreetheran et al., 2014). Consistent with our findings, in a survey-based study of inhabitants of major cities in China, perceived greenspace coverage was more strongly associated with better self-rated health and well-being in men than women (Li et al., 2020). However, in contrast with our findings, in British Columbia, Canada, greater park availability (assessed using an objective measure) was associated lower prevalence of a hypertension diagnosis in both males and females (Adhikari et al., 2021).

A nascent body of evidence suggests that green spaces are associated with lower rates of violent crime in neighborhoods (Branas et al., 2011, 2018; Kondo et al., 2017). Here, however, we postulated that higher crime rates might be a proxy measure for perceived safety, and that greater concerns about safety might reduce the benefits of green spaces. However, in contrast to our *a priori* hypotheses, results for the entire study population suggested the strongest protective associations between tree canopy and CVD mortality rates were in the highest crime rate neighborhoods. Further, protective associations between perceived park access and CVD mortality rates were restricted to the highest crime rate neighborhoods. It is possible that these stronger protective associations are explained by a variety of pathways, including by greenspace leading to improved social cohesion, social capital (Soga et al., 2017) or reduced stress levels (Roe et al., 2013).

In addition, we hypothesized that stronger protective associations in men versus women might be explained by women feeling more fearful in public spaces. Indeed, a growing body of evidence suggests that fear of crime is a barrier to greenspace utilization, particularly for women (Sreetheran et al., 2014). Gender based differences in park utilization have been shown to be mediated by greater perceptions of crime in women (Derose et al., 2019). Past studies have suggested that women are concerned about their safety when they visit green spaces alone (O'Brien, 2005). Yet, in this analysis, we did not observe strong evidence of differences in the interaction between crime rates (which we thought might be correlated with levels of perceived safety) and greenspace measures across sex categories. It is possible that, because of sparse numbers within some strata, we were under-powered to observe evidence of interaction. It is also possible that objective measures of neighborhood crime rates are not a strong marker for perceived safety. There is a critical need for future work, using larger data sets, and alternative measures of perceived safety, to further investigate the hypothesis that heterogeneity of associations between greenspace and CVD mortality across gender is explained by differences in safety perceptions.

To our knowledge, this is the first study of its kind to consider neighborhood crime rates as a modifier of sex-stratified associations of different greenspace measures and CVD mortality rates. This represents a critical step in identifying explanations for differences in relationships between greenspace and mortality outcomes according to categories of gender. Our study has several strengths. First, we examined associations with different types of greenspace, including vegetation cover (tree, grass/shrub, total) and perceived access to park/open spaces. This contrasts with most previous studies, which have estimated associations with overall greenness (e.g., NDVI) (Yuan et al., 2021). The measures of proportion tree canopy, grass/shrub, and total vegetation cover are derived from state of the art, high resolution land cover assessment data. We adjusted for neighborhood level covariates that might confound associations between the greenspace measures and CVD mortality rates. However, we acknowledge several limitations. We used an ecological study design, and calculated associations between tract-level measures of greenspace in year 2013 with CVD mortality rates. Although we had annual data on rates of CVD mortality, and time varying measures of greenspace, there were insufficient numbers of yearly deaths within each census tract to allow a year-level analysis. As a result, our results may be biased due to misclassification of greenspace measures, which may have changed over time. However, our results were robust, even after rerunning analyses using 2008 measures of greenspace. Further, exploratory analyses of changes in greenspace, over time, from year 2008–2018, suggested little change in amount, over time. Although we adjusted for several area level measures, it is possible that our estimates are biased due to residual confounding by unmeasured or inadequately measured factors. Additionally, results from this study do not imply causality, and, because of the ecologic design, should not be used to make inferences about associations at the person-level. In addition, although we included all residential Philadelphia tracts, we were unable to account for potential biases due to selection of healthier people into greener neighborhoods. Also, our measure of perceived park or open space access is subject to misclassification; because of the way the survey question on which the measure is based was asked, the variable may capture perceptions of non-green open spaces. Furthermore, the demographic characteristics of the respondents to the SEPHHS, which gave rise to the perceived park access measure, could be different and mis-represent perceptions of the population at risk of CVD mortality. Another limitation is that, because the unit of analysis was the residential census tract, of which there are only 374 in Philadelphia, we were underpowered to identify evidence of interaction, particularly in sex-stratified analyses. To maximize statistical power, we modeled the greenspace and crime variables as three level categorical terms, with categories based on tertiles of the distribution. Nevertheless, there were small numbers within certain strata. As a result, the stratified estimates of association are imprecise, and the results should be interpreted with caution. Relatedly, because we created the categories based on distributions of greenspace or crime rates within the city of Philadelphia, our results may not necessarily generalize to other cities where distributions of these variables may differ. Nevertheless, when considered in relative rather than absolute terms (comparison of lower to higher greenspace areas, or of lower to higher crime rate areas), our results provide important insights into the complex relationships between greenspace, crime, gender identity, and cardiovascular mortality.

5. Conclusion

Urban settings and public spaces involve complex interactions between personal identities, social contexts, and natural or built environments (Schinasi et al., 2024). Here, we have challenged conventional understanding of and research on links between greenspace and cardiovascular health by addressing potential heterogeneity of greenspace associations with CVD mortality rates, across contexts and identities. Our results point to gender-based differences in these associations, as well as variability according to levels of neighborhood crime. Further research that tests these hypotheses, using larger data sets and additional or improved measures of personal perception and identity (e.g., gender identity, sexual orientation, perceived prejudice, marginalization, or safety, etc.) is needed to inform effective and targeted population-based interventions that acknowledge and support differences across personal identities, neighborhoods, and contexts.

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CRediT authorship contribution statement

Wanyu Huang: Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Anneclaire J. De Roos:** Writing – original draft, Writing – review & editing. **Michelle C. Kondo:** Writing – review & editing. **Jane E. Clougherty:** Conceptualization, Writing – review & editing. **Yuzhe Zhao:** Data curation. **Leah H. Schinasi:** Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.healthplace.2024.103372.

Data availability

The authors do not have permission to share data.

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