Associations of objective and perceived greenness measures with cardiovascular risk factors in Philadelphia, PA: A spatial analysis

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Abstract:

There is mounting scientific evidence that greenness is associated with improved cardiovascular health. However, few studies have distinguished between vegetation type, measured perceived green space access, or investigated heterogeneity of associations across categories of neighborhood sociodemographic and racial/ethnic composition. We conducted an ecologic spatial analysis of associations of three objective measures of greenness (percent vegetation cover, percent tree canopy cover, and greenness density), and one measure of perceived access to green spaces with census tract level percentages of the adult population who were obese, ever had a high blood pressure diagnosis, and ever had a diabetes diagnosis, in the city of Philadelphia, PA, year 2013. We explored effect modification by census-tract level percent living in poverty and percent non-Hispanic Black categories. We used data from the Southeastern Pennsylvania Household Health Survey (SEPAHH) linked with high-resolution landcover, remotely sensed, and American Community Survey data and estimated associations using spatial lag models. We observed modest protective associations between percent of the adult population reporting perceived access to green spaces and percent with the cardiovascular risk factors, particularly in moderate and high poverty census tracts. Percent tree canopy cover was also protective against the cardiovascular risk factors, particularly in census tracts with low percentages of the population living in poverty and with low percent non-Hispanic Black populations. These results suggest that perceived access to green spaces and objectively measured high tree canopy cover, may protect against cardiovascular disease, but associations may vary across neighborhood sociodemographic categories.

Keywords:

Greenspace; vegetation, urban health, cardiovascular; cardiovascular; trees; NDVI; perceived access; socioeconomic status; race

Highlights:

- Perceived access to green spaces and high percent tree canopy cover were protective against CVD risk factors.

- The protective associations between perceived access to green spaces and CVD risk factors were restricted to census tracts with moderate or high percentages of the population living in poverty.
- The protective associations between percent tree canopy cover and CVD risk factors were restricted to census tracts with low percent non-Hispanic Black residents and low percentages of population living in poverty.

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1. Introduction

Cardiovascular disease (CVD) is the leading cause of mortality worldwide (Collaborators *et al*., 2018). Obesity (Body Mass Index > 30), high blood pressure, and diabetes are among the most important risk factors for CVD (Damen *et al*., 2016). These risk factors are associated with a modern urban lifestyle through different pathways, including living a sedentary life (Medina *et al.*, 2017), poor diet (Becerra-Tomás *et al*., 2020), exposure to air pollution (Bhatnagar, 2006) and noise (Swinburn *et al*., 2015), and urban sprawl (Chandrabose *et al*., 2019). Mounting scientific evidence also suggests that increased exposure to urban greenness is associated with reduced risk of being overweight (Müller *et al*., 2018), of having high blood pressure (Tamosiunas *et al*., 2014), or of having type 2 diabetes (Müller *et al*., 2018).

This growing evidence base has given rise to interest in the installation, renewal, and use of urban green spaces for population health promotion. Broadly, green infrastructure is a cultural and regulating ecosystem service that falls under the umbrella of "Nature-Based Solutions." Nature Based Solutions are nature-inspired actions, intended to address urban environmental challenges (Nesshöver et al., 2017; Lafortezza & Sanesi, 2019; Haase et al., 2014; Kabisch et al., 2017). Green infrastructure is a broad category, and it includes forests, green roofs, urban parks, street trees, and more. There is no consensus on the terminology that should be used to distinguish these different green space typologies, as evidenced by recent literature reviews (Knobel et al., 2019; Taylor & Hochuli, 2017). Here, we use the term greenness to describe any area with vegetation (e.g., grass, tree canopy, parks), and the term "green space" to refer to the subset of vegetated areas that are structured (e.g., parks or gardens). This terminology is consistent with past literature (Taylor & Hochuli, 2017), and the distinction between greenness and green space adds a layer of quality to the greenness concept (Markevych et al, 2017). For example, it distinguishes overgrown abandoned lots from pocket gardens, which may have different associations with human health due to their contrasting quality (Knobel et al, 2020).

Thus far, most research on links between greenness and health has estimated exposures using indices that represent overall greenness density, derived from remotely-sensed data. These remotely-sensed measures are easily accessible across all world regions and have a relatively high temporal resolution, allowing for easy use in multi-site, population-based studies. However, because they represent overall greenness density, they fail to discern different types of greenness (e.g., trees vs. grass) (Reid *et al.*, 2017) or measure perceived green space access. Different types of greenness may have different associations with health outcomes. For example, tree canopy has a greater potential to offer shade and improve thermal comfort than grass or shrubs (Armson et al., 2012). The potential effect of greenness on air quality may not require that the vegetation to be seen or used, as its presence, alone, could potentially have impacts on health (Nowak et al., 2006). In this case, objective measures, like surrounding greenness, may be more critical and better suited to exploring this potential health-promoting mechanism. On the other hand, for greenness to positively impact physical activity, it must be perceived to be usable, accessible, inclusive, and/or safe (Tabatabaie et al., 2019). Therefore, perceived measures would be a better fit in this case. Perceived and objective measures should not aim to be interchangeable and compared as equals (Leslie *et al.*, 2010). Perceived and objective metrics can, and should, be used as complementary measures (Moore *et al.*, 2008), especially when studying less explored mechanisms and outcomes. We use this approach in the current study.

Besides considering overall associations, it is also important to assess the heterogeneity of these relationships across categories of socioeconomic position or racial composition. Indeed, the direction and magnitude of associations may differ across categories of neighborhood sociodemographic composition for various reasons, including potential differential access, utilization, perception, quality, or experience of greenness and green spaces, among others (Wang et al., 2021; De Vries et al., 2020). Previous studies of the differences in relationships between greenness and health have arrived at conflicting conclusions, with some, but not all, suggesting greater benefits for low socioeconomic position populations (Mitchell & Popham, 2008; McEachan et al., 2016; Dadvand et al., 2012; Knobel et al, 2020, Browning et al., 2018). In addition to heterogeneity based on socioeconomic deprivation or poverty indicators, greenness may have distinct, differential impacts on cardiovascular health based on neighborhood racial/ethnic composition. Although race/ethnicity is correlated with socioeconomic position, these two constructs may modify associations between greenness and cardiovascular disease in different ways. Structural racism has resulted in the concentration of environmental pollutants, toxic stress, and low access to assets and resources (such as greenness) in racial/ethnic minority areas (Williams et al., 2009; Gee & Payne-Sturges, 2004). Racism may result in differential perception of safety or interaction with greenness and green spaces (Jones, 2000). Nevertheless, few studies, to date, have quantified heterogeneity of greenness-CVD relationships across neighborhood racial/ethnic composition categories.

In the present study, we used population-based survey data linked with several geospatial data sets to quantify associations of four different greenness measures (percent vegetation cover, percent tree canopy cover, overall greenness density, and percent of residents reporting perceived access to a park or outdoor space) with three CVD risk factors (obesity, high blood pressure diagnosis, and diabetes diagnosis). Additionally, we explored potential effect modification of these associations by neighborhood percent living in poverty and percent non-Hispanic Black.

2. Methods

2.1. Study setting and design

We conducted a neighborhood-level, ecologic analysis of associations between percent vegetation cover, percent tree canopy cover, overall greenness density (measured with NDVI), and perceived park and outdoor space access with three CVD risk factors: percent of adult residents with obesity, with a high blood pressure/hypertension diagnosis (ever), and with a diabetes diagnosis (ever). We used survey and geospatial data from several sources to conduct this analysis.

This study's setting was Philadelphia, PA, the sixth most populated and one of the poorest major cities in the United States (US Census Bureau). The distribution of greenness is heterogeneous across Philadelphia, making it an excellent setting for an analysis that depends on spatial contrasts (Schinasi, *et al*., 2019).

This study's analysis unit was the census tract, and all data were aggregated to 2010 census tract boundaries. Census tracts are small subdivisions of a county, defined by the US Census Bureau. They are commonly used in population-based research to approximate neighborhoods. In Philadelphia, census tracts are densely populated. For example, based on data from the American Community Survey (ACS) 2011-2015 five-year estimates, the average population density of a census tract was 7,390 people/km^2. We included all 377 populated census tracts in Philadelphia in the current analysis.

We selected year 2013 as the year for this study to optimize data availability from the different linked data sources. This year was also the median year between two land cover assessments that were conducted for the city of Philadelphia, which we used to estimate the percent of tree canopy and grass/shrub cover (described in detail below).

2.2. Data

The Southeastern Pennsylvania Household Health Survey (SEPAHH) is a biennial telephone survey administered by the Public Health Management Corporation and is conducted in five counties of southeastern Pennsylvania (Bucks, Chester, Delaware, Montgomery, and Philadelphia) (PHMC, 2015). For this study, we used data from Philadelphia County only. The survey data are collected through random digit dialing, with oversampling of people ages 60 and over. We used survey data collected from adult residents (ages 18+) in 2012 and 2014/2015; we assigned the average values from these two years as the value for the year 2013. We used survey data to estimate the percent of all residents in a census tract ages 18 years and older reporting perceived park or outdoor space access. The specific question on perceived park or outdoor space access was the following: "Is there a park or other outdoor space in your neighborhood that you are comfortable visiting during the day?". We also used survey data to estimate percentages of adults aged 18 years and older in each census tract who reported ever receiving a diabetes diagnosis, who reported ever having a high blood pressure/hypertension diagnosis, or who were obese. The percent reporting diabetes or high blood pressure diagnosis measures were based on survey questions that asked respondents if they had ever been told by a doctor or medical professional that they had the condition. The percent obese measure was based on self-reported height and weight. In our analyses, we used estimates that were smoothed using Bayesian hierarchical models that simultaneously account for spatial, temporal, and between race/ethnic dependence structures to account for the uncertainty resulting from using survey data to derive census tract-level estimates. The methods used to derive these smoothed estimates have been reported in detail elsewhere (Quick *et al.*, 2020). The exact

SEPAHH questions, responses, and coding of the included variables can be found in Table S1.

We used images from the Moderate-resolution Imaging Spectroradiometer (MODIS) of NASA's Terra satellite (MOD13Q1, Version 6 product) to derive normalized difference vegetation index (NDVI) estimates (Carroll *et al.*, 2004). These data are generated every 16 days at a 250-meter resolution. We used all images available from the year 2013 to calculate the annual mean greenness density value. A larger number of previous studies of links between greenness and cardiovascular disease have used MODIS-derived NDVI data (Yuan et al., 2020). Thus, this measure allows excellent comparison with previously conducted studies that have relied on MODIS captured NDVI data. The NDVI is a quantitative measure of greenness density, ranging in value from -1 to 1, with higher values indicating more photosynthetically active land cover. Its calculation is based on vegetated versus non-vegetated areas' reflectance properties: Healthy vegetation absorbs visible light but reflects near-infrared light, but non-vegetated areas reflect more visible light and less near-infrared light. Negative NDVI values represent water, values close to zero are areas without green (e.g., pavement), and those close to one are the most densely green areas. We used the Raster package's extract function (Hijmans & van Etten, 2012) of the R software (version 3.5.1) to calculate the mean NDVI value in each census tract, for each image capture. We then calculated the mean NDVI for the year of 2013 within each census tract.

We used high-resolution (30.5 cm × 30.5 cm) orthophotography and Light Detection and Ranging (LiDAR) based land cover data to calculate percent tree canopy cover and percent vegetation cover within each census tract. These data were based on land cover assessments conducted for the city of Philadelphia, for which each 1-foot pixel was assigned to the following seven mutually exclusive categories: (1) tree canopy, (2) grass/shrub, (3) bare earth, (4) water, (5) buildings, (6) roads, and (7) other paved surfaces. Percents were defined as the total area covered by tree canopy, for tree canopy cover, or tree canopy plus grass/shrub cover, for vegetation cover, divided by the total land area in each census tract (km^2). Two land cover assessments were conducted for Philadelphia; one was conducted in 2008 and the other in year 2018 (O'Neil-Dunne & Grove, 2011; O'Neil-Dunne *et al.*, 2013). We derived the 2013 estimates by linearly interpolating the values across the years.

Data on census tract-level population density, percent of the population living in poverty, and percent of the population who were non-Hispanic Black were derived from American Community Survey data for years 2011-2015 (US Census Bureau). The threshold for living in poverty is defined by the US Census Bureau and varies based on family size and composition.

2.3. Statistical analysis

Main analysis

We developed spatial lag models to estimate associations of percent tree canopy cover, percent vegetation cover, overall greenness (NDVI), and perceived park or outdoor space access with percentages of the adult population in the census tract who were obese or reported having diagnosed high blood pressure or diabetes. We used spatial lag models to account for potential spatial autocorrelation across census tract boundaries. Neighbors were defined using a first-order Queen contiguity matrix. We ran separate models for each combination of outcome and greenness measure, or twelve separate models in total. Given that we observed nonlinearity in the associations, we modeled the exposures as categorical variables, with the categories based on tertiles (Table 1). We treated the first tertile (low) as the reference category; our estimates represent the average change in the percentage of the census tract's population with the health outcome associated with moving from the first (low) to the second (medium) or the first to the third (high) tertile. We adjusted our models for the percent of the census tract population living in poverty, percent non-Hispanic Black, and population density, all coded as three-level categorical variables based on their tertiles (Table 1). We selected these variables, *a priori*, based on hypotheses that they might confound associations between greenness and cardiovascular risk factors.

Effect modification

We assessed potential effect modification of associations by percentages of the census tract population living below the poverty line and percent of non-Hispanic Black by including an interaction term between the primary explanatory variable (the exposure measure) and the potential effect modifier. We coded each modifier as a three-level categorical variable, with categories based on their tertiles (Table 1). We report stratified estimates for each one of the tertiles (low, medium, and high). We evaluated improvement in model fit and statistical evidence of effect modification by comparing AIC statistics from nested models, with and without the interaction terms.

We performed all analyses using R statistical software (RStudio Version 1.2.5033). We used the package spdep (Bivand *et al*., 2015) to run the spatial lag models.

3. Results

Descriptive statistics

There was substantial variability in population density and sociodemographic composition across census tracts, with a mean of 7527.3 inhabitants/km^2 (range: 0.2 – 25754.0 inhabitants/km$^{2)}$, 42.0 (range: 0.0 - 99.5) for percent non-Hispanic black population and 26.4 (range: 0.0 - 74.3) for percent of the population living in poverty. There was also substantial heterogeneity in the distribution of greenness across the census tracts; the mean values for NDVI, percent vegetation cover, and percent tree canopy cover were 0.29 (range: 0.06 – 0.63), 34.9 (range: 4.6 - 92.7), and 15.4 (range: 1.8 - 80.4), respectively. The mean percent of residents reporting having access to a park or outdoor space in their neighborhood was 75.2 (range: 45.3 - 94.9). On average, fewer than half of residents across census tracts were obese (Mean: 31.5, range: 16.9 - 41.0) or reported having a diagnosis of high blood pressure (Mean: 33.4. range 20.4 - 42.0). The mean percent reporting a diabetes diagnosis was lower, with, on average, less than one-fifth of the population in each census tract reporting this condition (Mean: 12.4 range 4.5 - 17.5) (TABLE 1).

TABLE 1: Descriptive statistics for the populated census tracts from Philadelphia, PA, included in this analysis.

Variable	**N = 377**
Population density (population/km^2)	
Mean (SD)	7527.3 (4415.1)
Median [min,max]	6860.5 [0.2, 25754.0]
Percent non-Hispanic Black	
Mean (SD)	42.0 (34.9)
Median [min, max]	29.6 [0.0, 99.5]

Percent of population living in poverty		
Mean (SD)		26.4 (15.7)
Median [min,max]		24.8 [0.0 , 74.3]
NDVI		
	Low	(0.06 - 0.23)
Tertiles	Medium	(0.23 - 0.33)
	High	(0.33 - 0.63)
	Mean (SD)	0.29 (0.11)
	Median [min,max]	0.27 [0.06, 0.63]
Percent vegetation cover		
	Low	4.6 – 26.6
Tertiles	Medium	26.7 – 39.2
	High	39.3 – 92.7
	Mean (SD)	34.9 (16.5)
	Median [min,max]	31.5 [4.6, 92.7]
Percent tree canopy cover		
	Low	1.8 – 9.5
Tertiles	Medium	9.5 – 15.9
	High	16.0 – 80.4
	Mean (SD)	15.4 (11.2)
	Median [min,max]	12.3 [1.8, 80.4]
Percept reporting perceived park or outdoor space access		
	Low	45.3 – 71.9
Tertiles	Medium	72.0 – 79.0
	High	79.1- 94.9
	Mean (SD)	75.2 (9.2)
	Median [min,max]	75.4 [45.3, 94.9]
Percent obese		
	Mean (SD)	31.5 (5.8)
	Median [min,max]	32.4 [16.9, 41.0]
Percent reporting high blood pressure diagnosis		
	Mean (SD)	33.4 (5.3)
	Median [min,max]	34.0 [20.4, 42.0]
Percent reporting diabetes diagnosis		
	Mean (SD)	12.4 (3.0)
	Median [min,max]	13.2 [4.5, 17.5]

All objective greenness measures were highly correlated, with correlation coefficients greater than 0.8 (TABLE 2). Percentage of adult residents reporting perceived park or outdoor space access was only moderately correlated with the objective measures, and most highly correlated with percent tree canopy (correlation coefficient: 0.32), followed by percent vegetation cover (correlation coefficient: 0.21) and least with NDVI (correlation coefficient: 0.12). The CVD risk factors were highly correlated with one another; correlation coefficients were higher than 0.9. Percentage of the population that was non-Hispanic Black population was moderately correlated with percent living in poverty (correlation coefficient: 0.41). A complete correlation matrix showing relationships between the greenness measures, health outcomes, and covariates is given in TABLE S2.

TABLE 2: Correlation matrix demonstrating relationships between the greenness measures.

	Percent tree canopy cover	**Percent vegetation cover**	**Overall greenness (NDVI)**	**Perceived access to green space (% of adults reporting)**
Percent tree canopy cover	1.00	0.88	0.81	0.32
Percent vegetation cover		1.00	0.95	0.21
Overall greenness (NDVI)			1.00	0.12
Perceived access to green space (% of adults reporting)				1.00

Main analysis

Results from spatial lag models estimating associations between percentage of the census tract's adult population reporting perceived park or outdoor space access, and objective measures of percent tree cover, percent vegetation cover, and NDVI with percentages of the adult population who were obese, who reported ever having a high blood pressure diagnosis, and who reported ever having a diabetes diagnosis, adjusted for census tract level population density, percent non-Hispanic Black, and percent of the population living in poverty, are presented in FIGURE 1 (Quantitative estimates are given in TABLE S3). Associations with all three outcomes followed similar patterns, with the strongest protective associations with percent obese, followed by percent reporting ever receiving a diagnosis of high blood pressure, and, finally, percent reporting ever receiving a diagnosis of diabetes. Estimates comparing the second to the first tertile were null or close to the null for all exposure and outcome combinations. However, we observed evidence of protective associations based on comparing the third vs. the first tertiles of exposure. Percent reporting perceived park or outdoor space access was protective against the cardiovascular risk factors (Beta: -2.68; 95% CI: -3.93, -1.43 for associations with percent obese, Beta: -2.13, 95% CI: -3.35, -0.9 for associations with percent with blood pressure diagnosis, Beta: -1.35 95% CI: -2.06, -0.64 for associations with percent with diabetes diagnosis). Percent tree canopy cover was also protective against the cardiovascular risk factors (Beta: -0.89; 95% CI: -2.05, -0.28 for associations with percent obese, Beta: -0.79 95% CI: -1.95, 0.37 for associations with percent with blood pressure diagnosis, Beta: -0.57 95% CI: -1.24, 0.1 for associations with percent with diabetes diagnosis). However, estimates of association with percent vegetation cover and NDVI were close to null.

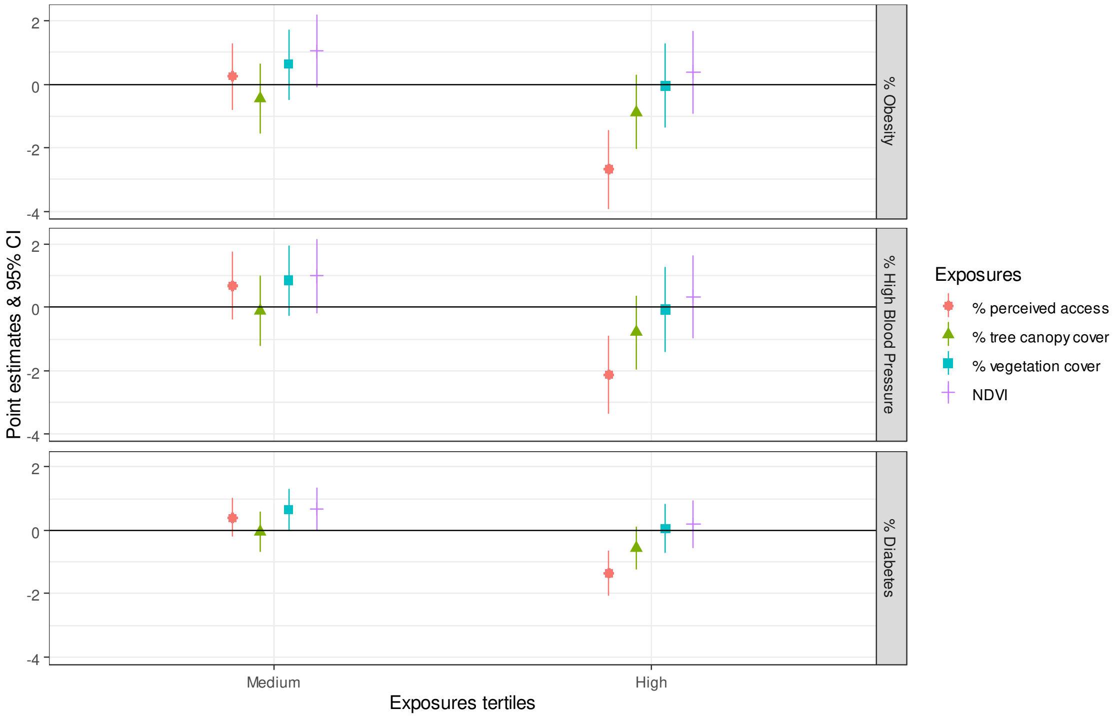

FIGURE 1: Estimates of association between the greenness measures and CVD risk factors, derived from spatial lag models adjusted for population density, percent living in poverty and percent non-Hispanic Black population.

Effect modification by sociodemographics

Stratified effect estimates were relatively imprecise with wide CIs, and we observed little statistical evidence effect modification of the greenness-CVD risk factor associations by neighborhood sociodemographic variables, based on examination of the

AIC statistics (Table S4). However, patterns in the magnitude and direction of the stratified estimates were suggestive of heterogeneity in some of the greenness-CVD risk factor associations across categories of percentage of the population living in poverty (FIGURE 2, Table S5) and percent of the population that was non-Hispanic Black (FIGURE 3, Table S6). Specifically, the protective association between percent reporting perceived access to parks or outdoor spaces and the CVD risk factors was restricted to medium and high percent poverty census tracts. For example, the protective association between percent reporting perceived park or outdoor space access and percent reporting a diagnosis of high blood pressure was restricted to high (Beta: -3.92, 95% CI: -6.42, -1.42) and medium (Beta: -2.08, 95% CI: -3.89, -0.28) percent poverty census tracts, but close to null in low % poverty areas (Beta: 0.46, 95% CI: -2.00, 2.93, Delta AIC after including interaction term: -0.919). By contrast, patterns suggested protective associations of percent tree canopy cover the CVD risk factors were restricted to the lowest poverty areas, although we did not observe statistical evidence of effect modification, based on comparison of AIC statistics from nested models. For example, high percent tree canopy cover appeared protective against obesity in low percent poverty census tracts (Beta: -2.39, 95% CI: -4.26, -0.52), and close to null in medium (Beta: -0.75, 95% CI: -2.66, 1.16) and high (Beta: 0.95, 95% CI: -1.15, 3.05) percent poverty areas. Similarly, the protective association between percent tree canopy cover and the CVD risk factors was restricted to census tracts with low % non-Hispanic Black populations. For example, high percent tree canopy was protective against percent obese in census tracts with low percentages of the population who were non-Hispanic Black (Beta: -2.38; 95% CI: -4.14,-0.62), but estimates of association between percent tree canopy and percent obese were close to null in census tracts with medium (Beta: -0.32, 95% CI: -2.08, 1.44) or high (Beta: -0.81, 95% CI: -2.70, 1.08) percent non-Hispanic Black populations (delta AIC following the inclusion of interaction term: -1.933, Table S4).

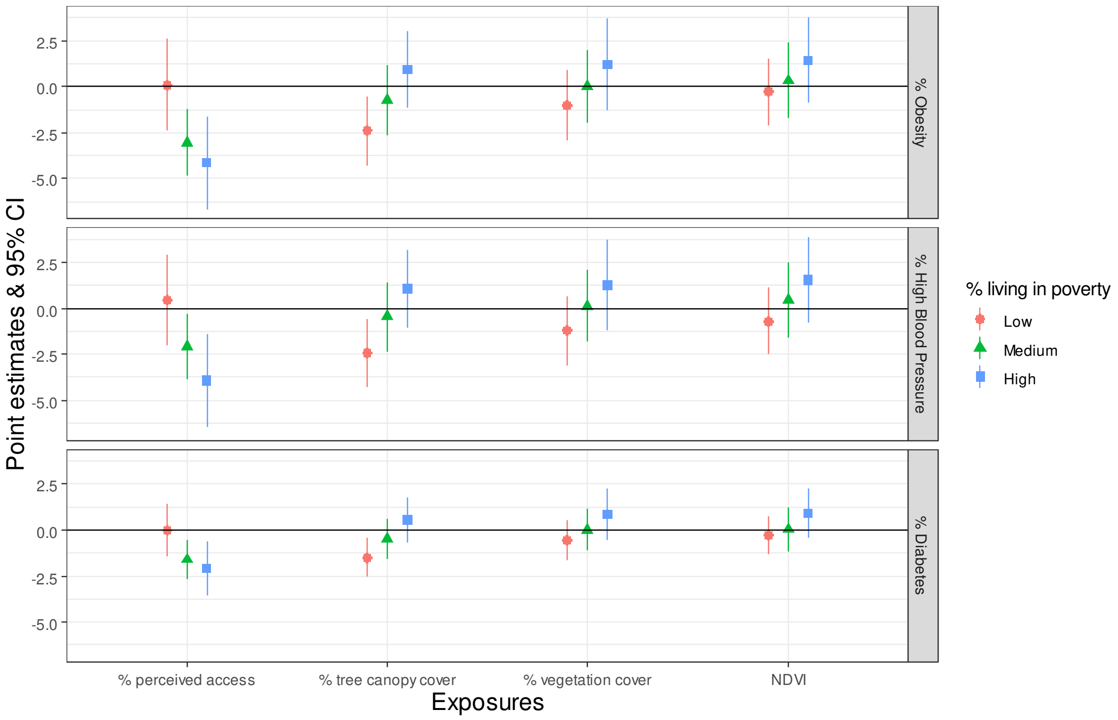

FIGURE 2: Stratified estimates of association between the greenness measures and CVD risk factors, derived from spatial lag models adjusted for population density, percent living in poverty and percent non-Hispanic Black population, and an interaction term between the greenness measures and percent of the population living in poverty. The estimates represent contrasts of the third vs. the first tertile of the greenness measure.

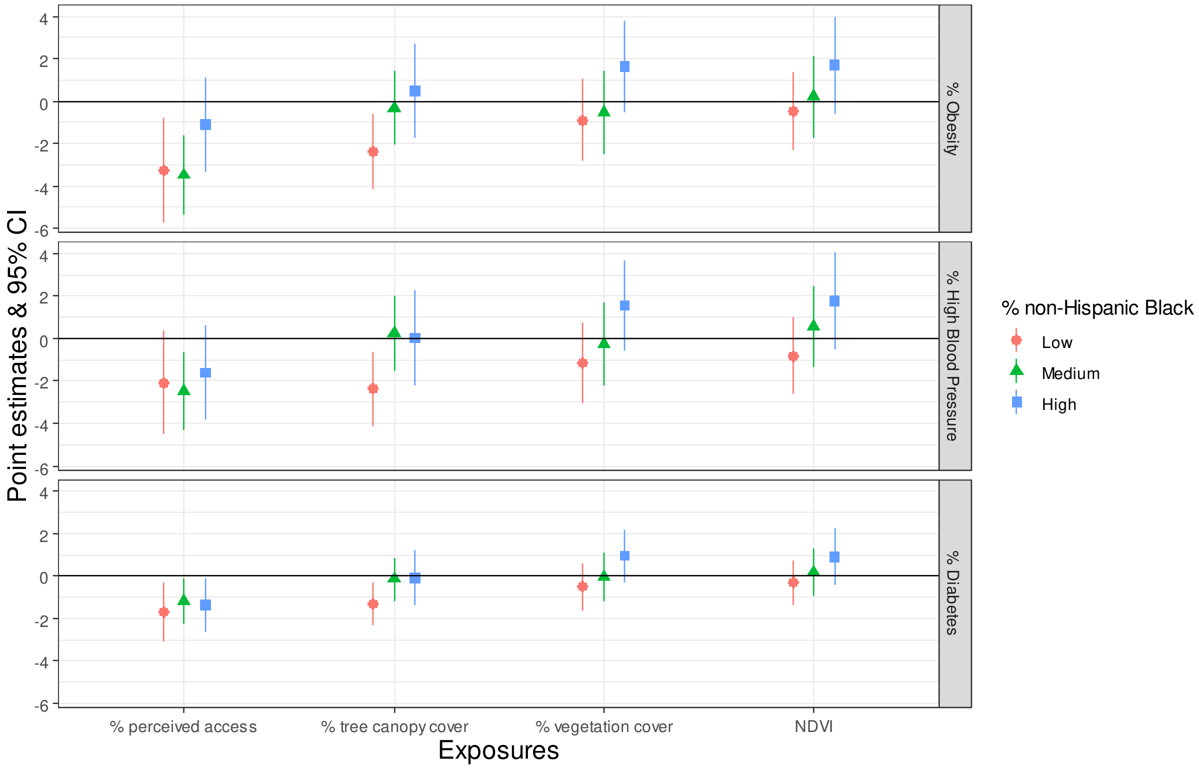

FIGURE 3: Stratified estimates of association between the greenness measures and CVD risk factors, derived from spatial lag models adjusted for population density, percent living in poverty and percent non-Hispanic Black population, and an interaction term between the greenness measures and percent non-Hispanic Black population.

4. Discussion

Results from this spatial analysis of associations of three objective measures of greenness, and one measure of perceived access to green spaces, with several CVD risk factors in Philadelphia, PA, suggest that greenness, and particularly perceived access to green space and higher percent tree canopy cover may protect against cardiovascular disease risk factors. These results contribute to mounting evidence of the salutogenic benefits of greenness. We also observed evidence that the protective association between perceived access to parks and outdoor spaces and CVD risk factors was restricted to census tracts with higher percentages of the population living in poverty. Meanwhile, the protective association between tree canopy cover and CVD risk factors was restricted to census tracts with low percent non-Hispanic Black populations.

We estimated the magnitude and direction of correlations of three different objective greenness measures with an estimate of perceived access to green space (park or outdoor spaces). There was low correlation between the perceived and objective greenness measures. This is consistent with previous analyses that have estimated correlations between objective and perceived greenness measures. For example, Orstad *et al*. (2017) reviewed the agreement between objective and perceived greenness metrics in physical activity studies, and 72.1% of the studies showed only slight-to-poor agreement (kappa = .00 - .40). There are several potential explanations for the low correlation between objective and perceived measures. The disagreement could be due to the green space question on the survey: questionnaires used to characterize green space perception may ascertain different dimensions of exposure, such as perceptions of access, utilization, and/or safety. For example, safety can be measured by perceived measures and not by objective measures, at least in a reliable way (Schipperijn *et al*., 2010). These perceived measures may play an important role in the association between greenness and human health, especially regarding the beneficial effects that rely on biological mechanisms. Reports of high levels of perceived access to safe green spaces within one's neighborhood may better correspond to actual utilization of green space. For example, a green space that is perceived as accessible and safe might better promote physical activity than one perceived as being difficult to access or unsafe. Similarly, a green space that is perceived as safe might harbor more social activities than one perceived as unsafe (McCormack et al., 2010).

Interestingly, of all the objective measures, percent tree canopy cover was most highly correlated with percentages of the adult population reporting perceived park or outdoor space access. This finding might indicate that tree canopy cover has important impacts on community's perception of green space access. Further research is needed to explore the reasons for the relatively low correlations between perceived and objective greenness measures. In addition, our results have implications for future research studies relying only on objective measures of greenness, as the interpretation of any results should consider the potential that the exposure estimates are not necessarily representative of actual perception of green space access or safety (or utilization of the green space).

The different greenness measures that we used in this study were estimated using different units (e.g., percent of residents reporting access to green space vs. % tree canopy cover vs. greenness density measured using an index measure), making it difficult, and potentially incorrect, to quantitatively compare the estimates of association across the different measures. However, the stronger magnitude of the estimates of association with the perceived vs. the objective measures suggested that perceived access to green spaces may be more important for cardiovascular health promotion compared to the objective greenness measures. This finding is consistent with the conclusions from a review paper by Orstad *et al*. (2017), which found that a higher percent of studies using perceived greenness measures found significant associations with physical activity compared to studies that used objective greenness measures. Also consistent with our results, Dadvand *et al*. (2016) found more robust associations with perceived park or outdoor space access than with residential surrounding greenness when analyzing associations with perceived general health, mental health, physical activity, and social cohesion. We also found that, of the objective greenness measures, percent tree canopy cover was most protective against CVD. This finding is consistent with previous research on the health benefits of tree canopy cover. For example, Ulmer *et al*. (2016) found that tree canopy cover was protective against self-reported overall health and that this association was mediated by a reduction in percent obese, diabetes, high blood pressure, and asthma. The finding is also consistent with research comparing tree canopy cover with other objective measures. In New York City, New York, USA, Reid *et al*. (2017) found a stronger beneficial association between percent tree canopy cover and self-reported health compared to percent overall vegetation.

Effect modification:

To our knowledge, our study was one of the first to quantify heterogeneity of associations between perceived and objective greenness measures and CVD across neighborhood sociodemographic composition variables. In particular, our examination of effect modification by percent non-Hispanic Black is an important contribution to literature on greenness and health links. We found that percent reporting perceived park or outdoor space access was protective against percent reporting ever having a high blood pressure diagnosis, but only in medium or high poverty census tracts. This finding is consistent with the equigenic hypothesis, that lower socioeconomic status groups could benefit the most from more greenness access and exposure (Mitchell et al., 2015). Consistent with our findings, a study from the United Kingdom observed lower inequality in circulatory disease mortality in populations living in the greenest areas (Mitchell & Popham, 2008). Similarly, another study from the United Kingdom found that a protective association between green space access and cardiovascular disease mortality was restricted to the most socioeconomically deprived subpopulations (Lachowycz & Jones 2014). By contrast, in a study of associations of quality of greenness with green space use, obesity, and physical activity in Barcelona (Spain), Knobel et al. (2020) found that greenness was more protective against obesity among participants with a high school education or higher. Other analyses have not observed heterogeneity of associations between NDVI or tree canopy cover and obesity across income levels (Browning *et al*., 2018). Lower-income populations may be exposed to several environmental or social stressors, such as air pollution (Hajat et al., 2015) or extreme heat (Harlan et al., 2006). Greenness exposure and access may be particularly important in impoverished areas by mitigating exposures to these stressors. Further research is needed to quantify the heterogeneity of associations between greenness and cardiovascular health across different neighborhood poverty levels and explore the mechanisms that give rise to any additional health promotion in more deprived areas.

In addition to quantifying effect modification by percent living in poverty, we also assessed heterogeneity across categories of neighborhood percent non-Hispanic Black population. In our data, percent living in poverty was only moderately correlated with percent non-Hispanic Black. Further, in general, these two indicators of sociodemographic composition represent different constructs. In particular, ethnic and racial minorities face different levels of racism (i.e., institutional, personally mediated) (Jones, 2000), which may contribute to different relationships between greenness and CVD. Here, we found that the protective association between percent tree canopy cover and percent obese was restricted to census tracts with low percent non-Hispanic Black populations. Literature regarding differences in greenness and human health associations by race/ethnicity is scarce and inconsistent, and few studies have considered heterogeneity across categories of neighborhood non-Hispanic Black composition. When considering pregnant women, Dadvand *et al*. (2014) found a positive association between greenness and birth outcomes, but only among white females, not among Pakistani origin mothers. Contrarily, McEachan *et al*. (2016) found no differences between ethnic groups in the association between greenness and depression during pregnancy. The reasons that ethnic/racial minority neighborhood residents may benefit less from greenness are complex and could be related to different levels of racism (Jones, 2000). For example, residential racial segregation, a legacy of structural racism in the United States, has led to the geographic concentration of social, built environment, and environmental stressors in ethnic or racial minority areas (Gee & Payne-Sturges). It may be that green space is not sufficient to overcome some of the other barriers to cardiovascular health in these neighborhoods, where residents are faced with such tremendous, and numerous, barriers to health and well-being. Besides, the health impact of objective measures of exposure to greenness may be mediated by personal perceptions, such as connectedness to greenness, which could, by itself, be associated with sociodemographic variables such as age, gender, ethnicity, or socioeconomic status (Shanahan *et al.*, 2016). Further, past research has indicated that ethnic and racial minorities have a greater fear of crime in green spaces compared to their white counterparts (Sreetheran & Van Den Bosch, 2014), suggesting differential utilization or perception across racial categories. Therefore, the association between greenness and human health might differ between census tracts with similar objective greenness levels but different racial/ethnic composition.

Strengths and limitations:

The strengths of this study include the estimation of associations with several distinct objective greenness measures and a survey-based measure of green space perception. The inclusion of these various measures is a particularly important contribution to this literature. We used spatial lag models to account for spatial autocorrelation and adjusted for several sociodemographic compositional factors, which we hypothesized might confound estimates. Finally, our stratification of analyses by two different sociodemographic constructs - percent living in poverty and percent non-Hispanic Black – is an important novelty and strength. Stratification by these two distinct sociodemographic variables improves understanding of the salutogenic effects of greenness by showcasing the importance of considering neighborhood context and composition. Urban decision-makers can use this information to inform their assessments and fine-tune their decisions to the specific context where they will take place.

We acknowledge several limitations of this study. Because this study was ecological, it is prone to the ecological fallacy. However, Philadelphia's census tracts are densely populated, and ecologic level exposures might approximate individual ones. Moreover, we cannot rule out reverse causation or bias due to self-selection, especially regarding perceived park or outdoor space access in that healthy people might have fewer requirements to define something as accessible or self-select themselves into living in greener areas. We tried to reduce confounding by controlling for race, poverty, and population density. However, like any other observational study, we cannot rule out the potential for residual confounding.

To estimate overall greenness in each census tract, we calculated a mean annual NDVI value, using all available images from the year 2013 of the MODIS Vegetation Indices (MOD13Q1) Version 6 data. The MOD13Q1 NDVI data are produced on 16-day intervals, and retrieved from daily, atmosphere-corrected, bi-directional surface reflectance. The Version 6 data use a MODIS-specific compositing method to remove low quality pixels (i.e., cloud contaminated and off-nadir sensor views). From the remaining high-quality pixels, it selects a single value per pixel using Contrained View Angle-Maximum Value Composite criteria (Didan et al., 2015). Despite these control efforts, the quality of each composited image, or of the pixels within each image, may still vary. In our processing of the images, we did not mask low-quality pixels, which may have led to some level of exposure misclassification.

This analysis included only 377 census tracts; thus, we were relatively underpowered to assess effect modification. As a result, the stratified effect estimates of association were relatively imprecise, with wide confidence limits. Some of the results from our analyses suggested interesting heterogeneity across sociodemographic categories, and further research with larger data sets is needed to further explore these differences.

The survey question we used to estimate perceived access to green space ("Is there a park or other outdoor space in your neighborhood that you are comfortable visiting during the day?") made use of a broad definition of green space and accessibility. Participants might be referring to non-green public open spaces instead of green spaces. On the other hand, this question allows for the capture of accessibility to spaces that are not defined explicitly, such as gardens or parks. Similarly, the definition of access is not limited to physical access, as it includes the concept of perceived comfort. Comfort is a construct that might include many factors, such as safety, maintenance, aesthetics, or amenities.

The use of self-reported height and weight could have resulted in misclassification of percent obese. However, previous studies have found a strong correlation between self-reported and objective measures of BMI (McAdams, Van Dam, & Hu, 2007). Ever having been diagnosed with high blood pressure and or with diabetes were also based on self-reported survey data, which could have led to misclassification. However, we hypothesize that the use of questions, including explicit mentions of a medical diagnosis, reduces the risk of misclassification. Additionally, the outcomes have been smoothed at the census tract level using Bayesian hierarchical models and should not be interpreted as direct measures.

5. Conclusion

Our results suggest that tree canopy cover and perceived park or outdoor space access may improve urban area residents' cardiovascular health. Urban greening strategies that increase the amount of green in an area and particularly those that aim to make it more accessible, safe, inclusive and usable, may provide additional health benefits. Our results also suggest that any CVD protective effects of greenery may be heterogeneous and vary based on neighborhood sociodemographic composition. Choosing the best option between increasing the amount of green or facilitating access to the existing one might depend on the sociodemographic context.

Further research with larger data sets is needed to explore, more deeply, the reasons for heterogeneity across sociodemographic groups and to disentangle how sociodemographic factors modify salutogenic pathways. Lastly, further research using individual-level data are needed to confirm our results, especially those comparing perceived access to green space with objective greenness measures.

References:

Armson, D., Stringer, P., & Ennos, A. R. (2012). The effect of tree shade and grass on surface and globe temperatures in an urban area. *Urban Forestry & Urban Greening*, 11(3), 245-255.

Becerra-Tomás, N., Blanco Mejía, S., Viguiliouk, E., Khan, T., Kendall, C. W. C., Kahleova, H., … Salas-Salvadó, J. (2020, April 11). Mediterranean diet, cardiovascular disease and mortality in diabetes: A systematic review and meta-analysis of prospective cohort studies and randomized clinical trials. *Critical Reviews in Food Science and Nutrition*, Vol. 60, pp. 1207–1227. https://doi.org/10.1080/10408398.2019.1565281

Berrocal, V. J., Gelfand, A. E., & Holland, D. M. (2010a). A bivariate space-time downscaler under space and time misalignment. *The Annals of Applied Statistics*, *4*(4), 1942.

Berrocal, V. J., Gelfand, A. E., & Holland, D. M. (2010b). A spatio-temporal downscaler for output from numerical models. *Journal of Agricultural, Biological, and Environmental Statistics*, *15*(2), 176–197.

Bhatnagar, A. (2006). Environmental Cardiology. *Circulation Research*, *99*(7), 692–705. https://doi.org/10.1161/01.RES.0000243586.99701.cf

Bivand, R., Altman, M., Anselin, L., Assunção, R., Berke, O., Bernat, A., & Blanchet, G. (2015). Package' spdep.' *See Ftp://Garr. Tucows. Com/Mirrors/CRAN/Web/Packages/Spdep/Spdep. Pdf (Accessed 9 December 2015).*

Browning, M. H., & Rigolon, A. (2018). Do income, race and ethnicity, and sprawl influence the greenspace-human health link in city-level analyses? Findings from 496 cities in the United States. *International journal of environmental research and public health*, 15(7), 1541.

De Vries, S., Buijs, A. E., & Snep, R. P. (2020). Environmental Justice in The Netherlands: Presence and Quality of Greenspace Differ by Socioeconomic Status of Neighbourhoods. *Sustainability*, 12(15), 5889.

Carroll, M. L., DiMiceli, C. M., Sohlberg, R. A., & Townshend, J. R. G. (2004). 250m MODIS normalized difference vegetation index. *University of Maryland, College Park, Maryland.*

Chandrabose, M., Rachele, J. N., Gunn, L., Kavanagh, A., Owen, N., Turrell, G., … Sugiyama, T. (2019). Built environment and cardio-metabolic health: systematic review and meta-analysis of longitudinal studies. *Obesity Reviews*, *20*(1), 41–54. https://doi.org/10.1111/obr.12759

Collaborators, G. B. D. C. of D., Roth, G. A., Abate, D., Abate, K. H., Abay, S. M., Abbafati, C., … Badawi, A. (2018). *Global, regional, and national age-sex-specific mortality for 282 causes of death in 195 countries and territories, 1980–2017: a systematic analysis for the Global Burden of Disease Study 2017.*

Dadvand, P., de Nazelle, A., Figueras, F., Basagaña, X., Su, J., Amoly, E., Jerrett, M., Vrijheid, M., Sunyer, J. and Nieuwenhuijsen, M.J., (2012). Green space, health inequality and pregnancy. *Environment international*, 40, 110-115.

Dadvand, P., Bartoll, X., Basagaña, X., Dalmau-Bueno, A., Martinez, D., Ambros, A., Cirach, M., Triguero-Mas, M., Gascon, M., Borrell, C. and Nieuwenhuijsen, M.J. (2016). Green spaces and General Health: Roles of mental health status, social support, and physical activity. *Environment International*, *91*, 161–167. https://doi.org/10.1016/j.envint.2016.02.029

Damen, J. A. A. G., Hooft, L., Schuit, E., Debray, T. P. A., Collins, G. S., Tzoulaki, I., … Moons, K. G. M. (2016, May 16). Prediction models for cardiovascular disease risk in the general population: Systematic review. *BMJ (Online)*, Vol. 353. https://doi.org/10.1136/bmj.i2416

Didan, K., Barreto Munoz, A., Solano, R., & Huete, A. MODIS Vegetation index user’s guide (MOD13 Series): Version 3.00. June 2015 (Collection 6). Retried March 3, 2021, from https://lpdaac.usgs.gov/documents/103/MOD13_User_Guide_V6.pdf

Fang, C. F., & Ling, D. L. (2005). Guidance for noise reduction provided by tree belts. *Landscape and Urban Planning*, *71*(1), 29–34. https://doi.org/10.1016/j.landurbplan.2004.01.005

Gee, G. C., & Payne-Sturges, D. C. (2004). Environmental health disparities: a framework integrating psychosocial and environmental concepts. *Environmental health perspectives*, 112(17), 1645-1653.

Haase, D., Larondelle, N., Andersson, E., Artmann, M., Borgström, S., Breuste, J., Gomez-Baggethun, E., Gren, Å., Hamstead, Z., Hansen, R. and Kabisch, N. (2014). A quantitative review of urban ecosystem service assessments: concepts, models, and implementation. *Ambio*, 43(4), 413-433.

Hajat, A., Hsia, C., & O'Neill, M. S. (2015). Socioeconomic disparities and air pollution exposure: a global review. *Current environmental health reports*, 2(4), 440-450.

Harlan, S. L., Brazel, A. J., Prashad, L., Stefanov, W. L., & Larsen, L. (2006). Neighborhood microclimates and vulnerability to heat stress. *Social science & medicine*, 63(11), 2847-2863.

Hijmans, R. J., & van Etten, J. (2012). *raster: Geographic analysis and modeling with raster data. R package version 2.0–12*.

Jones, C. P. (2000). Levels of racism: a theoretic framework and a gardener's tale. *American journal of public health*, 90(8), 1212.

Kabisch, N., van den Bosch, M., & Lafortezza, R. (2017). The health benefits of nature-based solutions to urbanization challenges for children and the elderly–A systematic review. *Environmental research*, 159, 362-373.

Knobel, P., Dadvand, P., & Maneja-Zaragoza, R. (2019). A systematic review of multi-dimensional quality assessment tools for urban green spaces. *Health and Place*, *59*. https://doi.org/10.1016/j.healthplace.2019.102198

Knobel, P., Maneja, R., Bartoll, X., Alonso, L., Bauwelinck, M., Valentin, A., … Dadvand, P. (2020). Quality of Urban Green Spaces Influences Residents' Use of These Spaces, Physical Activity, and Overweight/Obesity. *Environmental Pollution*, 116393. https://doi.org/10.1016/j.envpol.2020.116393

Kondo, M. C., Han, S. H., Donovan, G. H., & MacDonald, J. M. (2017). The association between urban trees and crime: Evidence from the spread of the emerald ash borer in Cincinnati. *Landscape and Urban Planning*, *157*, 193–199. https://doi.org/10.1016/j.landurbplan.2016.07.003

Lachowycz, K., & Jones, A. P. (2014). Does walking explain associations between access to greenspace and lower mortality?. *Social science & medicine*, 107, 9-17.

Lafortezza, R., & Sanesi, G. (2019). Nature-based solutions: Settling the issue of sustainable urbanization. *Environmental research*, 172, 394-398.

Leslie, E., Sugiyama, T., Ierodiaconou, D., & Kremer, P. (2010). Perceived and objectively measured greenness of neighbourhoods: Are they measuring the same thing? *Landscape and Urban Planning*, *95*, 28–33. https://doi.org/10.1016/j.landurbplan.2009.11.002

Markevych, I., Schoierer, J., Hartig, T., Chudnovsky, A., Hystad, P., Dzhambov, A.M., De Vries, S., Triguero-Mas, M., Brauer, M., Nieuwenhuijsen, M.J. and Lupp, G., (2017). Exploring pathways linking greenspace to health: Theoretical and methodological guidance. *Environmental research*, 158, 301-317.

McAdams, M. A., Van Dam, R. M., & Hu, F. B. (2007). Comparison of Self-reported and Measured BMI as Correlates of Disease Markers in US Adults*. *Obesity*, *15*(1), 188–188. https://doi.org/10.1038/oby.2007.504

McCormack, G. R., Rock, M., Toohey, A. M., & Hignell, D. (2010). Characteristics of urban parks associated with park use and physical activity: A review of qualitative research. *Health & place*, 16(4), 712-726.

McEachan, R.R.C., Prady, S.L., Smith, G., Fairley, L., Cabieses, B., Gidlow, C., Wright, J., Dadvand, P., Van Gent, D. and Nieuwenhuijsen, M.J. (2016). The association between green space and depressive symptoms in pregnant women: moderating roles of socioeconomic status and physical activity. *J Epidemiol Community Health*, 70(3), 253-259.

Medina, C., Tolentino-Mayo, L., López-Ridaura, R., & Barquera, S. (2017). Evidence of increasing sedentarism in Mexico City during the last decade: Sitting time prevalence, trends, and associations with obesity and diabetes. *PLOS ONE*, *12*(12), e0188518. https://doi.org/10.1371/journal.pone.0188518

Mitchell, R. J., Richardson, E. A., Shortt, N. K., & Pearce, J. R. (2015). Neighborhood environments and socioeconomic inequalities in mental well-being. *American journal of preventive medicine*, 49(1), 80-84.

Mitchell, R., & Popham, F. (2008). Effect of exposure to natural environment on health inequalities: an observational population study. *The lancet*, 372(9650), 1655-1660.

Moreira, T. C. L., Polizel, J. L., Santos, I. de S., Silva Filho, D. F., Bensenor, I., Lotufo, P. A., & Mauad, T. (2020). Green Spaces, Land Cover, Street Trees and Hypertension in the Megacity of São Paulo. *International Journal of Environmental Research and Public Health*, *17*(3), 725. https://doi.org/10.3390/ijerph17030725

Müller, G., Harhoff, R., Rahe, C., & Berger, K. (2018). Inner-city green space and its association with body mass index and prevalent type 2 diabetes: A cross-sectional study in an urban German city. *BMJ Open*, *8*(1), 19062. https://doi.org/10.1136/bmjopen-2017-019062

Nesshöver, C., Assmuth, T., Irvine, K.N., Rusch, G.M., Waylen, K.A., Delbaere, B., Haase, D., Jones-Walters, L., Keune, H., Kovacs, E. and Krauze, K., (2017). The science, policy and practice of nature-based solutions: An interdisciplinary perspective. *Science of the Total Environment*, 579, 1215-1227.

Nowak, D. J., Crane, D. E., & Stevens, J. C. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban forestry & urban greening*, 4(3-4), 115-123.

O'Neil-Dunne, J., & Grove, J. M. (2011). A report on the City of Philadelphia's existing and possible tree canopy. *USDA Forest Service: Washington, DC, USA*.

O'Neil-Dunne, J. P. M., MacFaden, S. W., Royar, A. R., & Pelletier, K. C. (2013). An object-based system for LiDAR data fusion and feature extraction. *Geocarto International*, *28*(3), 227–242.

OpenDataPhilly. Retrieved August 17, 2020, from https://www.opendataphilly.org/

Orstad, S. L., McDonough, M. H., Stapleton, S., Altincekic, C., & Troped, P. J. (2017). A systematic review of agreement between perceived and objective neighborhood environment measures and associations with physical activity outcomes. *Environment and Behavior*, 49(8), 904-932.

PHMC. (2015). Public Health Management Corporation Community Health Data Base's Southeastern Pennsylvania Household Health Survey. Retrieved from http://www.chdbdata.org/..

Quick, H., Terloyeva, D., Wu, Y., Moore, K., & Roux, A. V. D. (2020). Trends in Tract-Level Prevalence of Obesity in Philadelphia by Race-Ethnicity, Space, and Time. *Epidemiology*, *31*(1), 15–21.

Reid, C., Clougherty, J., Shmool, J., & Kubzansky, L. (2017). Is All Urban Green Space the Same? A Comparison of the Health Benefits of Trees and Grass in New York City. *International Journal of Environmental Research and Public Health*, *14*(11), 1411. https://doi.org/10.3390/ijerph14111411

Sanusi, R., Johnstone, D., May, P., & Livesley, S. J. (2016). Street Orientation and Side of the Street Greatly Influence the Microclimatic Benefits Street Trees Can Provide in Summer. *Journal of Environmental Quality*, *45*(1), 167–174. https://doi.org/10.2134/jeq2015.01.0039

Schinasi, L. H., Quick, H., Clougherty, J. E., & De Roos, A. J. (2019). Greenspace and

Infant Mortality in Philadelphia, PA. *Journal of Urban Health*, *96*(3), 497–506. https://doi.org/10.1007/s11524-018-00335-z

Schipperijn, J., Ekholm, O., Stigsdotter, U. K., Toftager, M., Bentsen, P., Kamper-Jørgensen, F., & Randrup, T. B. (2010). Factors influencing the use of green space: Results from a Danish national representative survey. *Landscape and Urban Planning*, *95*(3), 130–137. https://doi.org/10.1016/j.landurbplan.2009.12.010

Sreetheran, M., & Van Den Bosch, C. C. K. (2014). A socio-ecological exploration of fear of crime in urban green spaces–A systematic review. *Urban Forestry & Urban Greening*, 13(1), 1-18.

Swinburn, T. K., Hammer, M. S., & Neitzel, R. L. (2015). Valuing Quiet: An Economic Assessment of US Environmental Noise as a Cardiovascular Health Hazard. *American Journal of Preventive Medicine*, *49*(3), 345–353. https://doi.org/10.1016/j.amepre.2015.02.016

Tabatabaie, S., Litt, J. S., & Carrico, A. (2019). A Study of Perceived Nature, Shade and Trees and Self-Reported Physical Activity in Denver. *International journal of environmental research and public health,* 16(19), 3604.

Tamosiunas, A., Grazuleviciene, R., Luksiene, D., Dedele, A., Reklaitiene, R., Baceviciene, M., … Nieuwenhuijsen, M. J. (2014). Accessibility and use of urban green spaces, and cardiovascular health: Findings from a Kaunas cohort study. *Environmental Health: A Global Access Science Source*, *13*(1), 1–11. https://doi.org/10.1186/1476-069X-13-20

Taylor, L., & Hochuli, D. F. (2017). Defining greenspace: Multiple uses across multiple disciplines. *Landscape and Urban Planning*, *158*, 25–38. https://doi.org/10.1016/J.LANDURBPLAN.2016.09.024

Ulmer, J. M., Wolf, K. L., Backman, D. R., Tretheway, R. L., Blain, C. J., O'Neil-Dunne, J. P., & Frank, L. D. (2016). Multiple health benefits of urban tree canopy: The mounting evidence for a green prescription. *Health and Place*, *42*, 54–62. https://doi.org/10.1016/j.healthplace.2016.08.011

US Census Bureau. *American community survey (ACS).* Retrieved from https://www.census.gov/programs-surveys/acs/

US Census Bureau. *Glossary*. Retrieved from https://www.census.gov/programs-surveys/geography/about/glossary.html

US Census Bureau. *How the Census Bureau Measures Poverty*. Retrieved from https://www.census.gov/topics/income-poverty/poverty/guidance/poverty-measures.html

US Census Bureau. *QuickFacts: Philadelphia County, Pennsylvania*. Retrieved September 29, 2020, from https://www.census.gov/quickfacts/philadelphiacountypennsylvania

Wang, R., Feng, Z., Pearce, J., Yao, Y., Li, X., & Liu, Y. (2021). The distribution of greenspace quantity and quality and their association with neighbourhood socioeconomic conditions in Guangzhou, China: A new approach using deep learning method and street view images. *Sustainable Cities and Society*, 66, 102664.

Williams, D. R., Sternthal, M., & Wright, R. J. (2009). Social determinants: taking the social context of asthma seriously. *Pediatrics*, 123(Supplement 3), S174-S184.

Yuan, Y., Huang, F., Lin, F., Zhu, P., & Zhu, P. (2020). Green space exposure on mortality and cardiovascular outcomes in older adults: a systematic review and meta-analysis of observational studies. *Aging Clinical and Experimental Research*, 1-15.