Greenspace and Infant Mortality in Philadelphia, PA

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Abstract Despite mounting evidence that urban greenspace protects against mortality in adults, few studies have explored the relationship between greenspace and death among infants. Here, we describe results from an analysis of associations between greenness and infant mortality in Philadelphia, PA. We used images of the normalized difference vegetation index (NDVI), derived from processed satellite data, to estimate greenness density in each census tract. We linked these data with census tract level counts of total infant mortality cases ($n=963$) and births ($n=113,610$) in years 2010–2014, and used Bayesian spatial areal unit, conditional autoregressive models to estimate associations between greenness and infant mortality. The models included a set of random effects to account for spatial autocorrelation between neighboring census tracts. Infant mortality counts were modeled using a Poisson distribution, and the logarithm of total births in each census tract was specified as the offset term. The

following variables were included as potential confounders and effect modifiers: percentage non-Hispanic black, percentage living below the poverty line, an indicator of housing quality, and population density. In adjusted models, the rate of infant mortality was 27% higher in less green compared to more green tracts (95% CI 1.02–1.59). These results contribute further evidence that greenspace may be a health promoting environmental asset.

Keywords Greenspace · Urban health · Urban landscape · Infant mortality · Epidemiology · Spatial · Geospatial

Introduction

The world is urbanizing at a record high pace [1], and there is great interest in exploring the role of the natural landscape in promoting health. Mounting evidence supports a link between greenspace—trees, parks, shrubs, grass—and improved health [2]. Indeed, research has shown that greenspace protects against all-cause mortality [3], and promotes mental [4, 5] and cardiovascular health [6], among other positive effects. A variety of mechanisms have been proposed to explain these associations, including reducing stress [7], buffering noise [8] and air pollution [9], reducing heat islands [10], lessening violent crime [11, 12], promoting social cohesion [13], and motivating physical activity [14].

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Exploring links between greenspace and infant mortality, defined as any death in children under 1 year of age, is of particular interest because infant mortality is regarded as a highly sensitive indicator of population health [15]. This is because factors that impact overall population health—economic deprivation, and environmental and living conditions, for example—predict infant mortality [15]. For example, income inequality [16], psychosocial stress [17], higher ambient temperatures [18], and air pollution [19] have all been linked with higher risk of adverse pregnancy outcomes or infant mortality. In the city of Chicago, IL, U.S., police district violent crime rates, poverty, and limited community access to primary medical care were associated with racial disparities in infant mortality [20].

To date, most epidemiologic studies of the mortality impacts of greenspace have focused on adults [3]. To our knowledge, only one previous study has explored the impact of greenspace on infant mortality. Specifically, in an analysis of data from Lyon, France, Kihal-Talantikite et al. [21] found suggestive evidence that proportions of total area census block covered by greenspace, estimated using land cover data and categorized according to tertiles, partially explained spatial clusters of infant mortality.

There are a number of mechanisms by which greenspace may protect against infant mortality. First, greenspace may prevent adverse birth outcomes, which are strong predictors of infant mortality. For example, prenatal exposure to greenspace has been shown to prevent several adverse birth outcomes, including low birth weight [22–24] and preterm birth [25], both of which are leading causes of infant mortality [26]. In addition, early life (post-natal) exposures to greenspace may prevent infant mortality by lowering air pollution [9, 27], noise [28], or heat [29], all of which have been associated with increased risk of infant mortality [18, 30, 31]. Greenspace may also protect against infant mortality by promoting social cohesion, which, in the health literature, is hypothesized to improve well-being by increasing access to services and resources, reducing psychosocial stress, and promoting the uptake of healthy behaviors [32].

Philadelphia, PA, a large city on the east coast of the USA, is an important setting in which to consider the impacts of greenspace on infant mortality. Philadelphia is the fifth largest city in the USA [33] and is characterized by high amounts of variability in greenspace. In an analysis based on LiDAR and high-resolution aerial

imagery data, Philadelphia was estimated to have 2.9 million trees and 20% tree canopy coverage in year 2012 [34]. Broken down by neighborhood, percentages of tree canopy cover ranged from 2.4 to 83.7%. In previous Philadelphia based analyses, census tract level median household income was strongly predictive of overall greenness levels in some, but not all, Philadelphia neighborhoods [33]. In 2009, the city launched its Greenworks program, to become the “greenest city in America.” As part of Greenworks, the city committed to a variety of programs, including tree planting, green stormwater infrastructure installation, green roofing, and vacant lot greening [35].

Philadelphia also has higher rates of infant mortality compared to rest of the nation. For example, in year 2014, rates of infant mortality were 7.8/1000 live births [36] in Philadelphia vs 5.8 per 1000 in the USA [37]. Although the infant mortality rate in Philadelphia has declined in recent years (e.g., down from 10.7 per 1000 births in 2010), racial disparities in infant mortality are vast and have increased [36].

Here, we describe results from an analysis of associations between greenspace and infant mortality in Philadelphia, PA, for years 2010–2014. We considered associations overall, and across levels of several sociodemographic compositional indicators, including poverty, race/ethnicity, population density, and housing quality.

Methods

The study period for this analysis was years 2010–2014. These years were selected to allow a sufficient sample size. Meanwhile, the time period was short enough to avoid issues introduced by major changes in the underlying population or in greenness levels within census tracts.

Greenness Measure

We estimated greenness levels using satellite images of the normalized difference vegetation index (NDVI). The NDVI is a quantitative measure of overall greenness density, ranging in value from -1 to 1 . The NDVI is based on the reflectance properties of vegetated versus non-vegetated areas; healthy vegetation absorbs most visible light and reflects most near infrared light, whereas non-vegetated areas reflect more visible light and less

near-infrared light [38]. Negative NDVI values represent water, values close to zero are areas without green (e.g., pavement in urban areas), and values close to one represent the most densely green areas. For reference, in July of the year 2011, the mean NDVI value for 59,483 U.S. census tracts in metropolitan areas containing $\geq 100,000$ people was 0.55 (standard deviation 0.18) [39]. We downloaded the NDVI images from the moderate-resolution imaging spectroradiometer (MODIS) of NASA's Terra satellite (MOD13Q1, Version 6 product). MODIS provides 250-m images for every 16-day period of each year.

We used the median NDVI in each census tract, based on all images taken during year 2012 (the median for the study period). We elected to use the median NDVI to represent the central tendency for the entire year. However, preliminary analyses showed that the mean and median NDVI values in each census tract were highly correlated ($R^2 > 99\%$). We used images from the year 2012 because, in preliminary analyses, we observed extremely high correlations across years ($R^2 \geq 98\%$), indicating that the value from 2012 was representative of the entire time period and sufficient to represent the spatial variability of greenness over the study period, which was the focus of this analysis. We processed the NDVI images using the `extract` function within the raster package of the R software (version 3.5.1) [40], which returns the median values for all 250-m grid cells covered by a census tract polygon. The function includes in its calculation any cell whose center is located inside the polygon. We did not exclude any NDVI values (i.e., we included in our calculation of the median any values that were zero or negative).

Birth and Mortality Data

We used census tract level counts of infant mortality and total births, as reported by the City of Philadelphia's Department of Public Health [41]. Infant deaths were defined as all deaths that occurred in children younger than the age of one. To avoid unstable rates due to small counts, we aggregated the total number of infant deaths and births within each census tract across the 2010–2014 study period. Such an approach of aggregating births and infant deaths across years to accommodate small counts has been taken previously [42].

Analysis

We investigated the association between greenness and infant mortality using Bayesian models that account for spatial structure. Specifically, we used the conditional autoregressive model of Besag et al. [43], which models the spatial pattern in the response as a function of covariates, and a combination of spatial and non-spatial random effects. The spatial random effects shrink rates for a given census tract based on values in neighboring tracts, and account for any spatial autocorrelation that remains after the covariates have been accounted for [44, 45]. All analyses were conducted using the CARBayes package [46] in R, version 3.4.0 [47]. As is common in Bayesian inference, the models were fit using Markov chain Monte Carlo (MCMC) methods, which are iterative algorithms for sampling from a probability distribution. The algorithms must first be run for a long enough time to achieve convergence (often referred to as the “burn-in period”) and then run on additional samples to be used for inferential purposes. Here, we assessed convergence using 10,000 MCMC samples; inference was then made using the posterior mean and 95% credible interval (95% CI) based on an additional 90,000 MCMC samples (for a total of 100,000). We assumed a Poisson distribution to model the counts of infant mortality and treated the number of total births in each tract as an offset term.

In full models, we adjusted for indicators of area-level poverty, racial/ethnic composition, housing quality, and urbanicity. We also investigated these as potential effect modifiers by including interaction terms between the term for greenness and each of the covariates (in separate models). All of these variables have been associated with either infant mortality or adverse birth outcomes [48–51], and we selected them for inclusion based a priori hypotheses that they might confound or modify relationships with greenspace. The specific covariate measures were 2010–2014 American Community Survey [52] estimates of census tract level percent Black-non-Hispanic, percent living below the poverty line, and population density (used as an indicator of urbanicity). The US Census Bureau bases its definition of living below the poverty line on income thresholds that vary depending upon family size and composition [53]. If a family's total income is below the relevant threshold, then that family is classified as living below the poverty line. The housing quality indicator was defined as the percentage of residential

properties in each census tract that had below average exterior condition. The variable was based on the City of Philadelphia's Office of Property Assessment's data, which were downloaded from Philadelphia's open data portal in year 2016 [54]. The Office of Property Assessment assesses the exterior condition of housing structures, for tax purposes, and classifies it into one of the following categories: new construction, new rehabilitated, above average, average, below average, vacant but habitable, and sealed and structurally compromised. The classifications are based on comparisons with other properties in the Geographic Market Area. Property assessments are conducted for distinct sections of the city in each year, and then repeated on a rolling basis. Based on the distribution of years for which the property assessments were reported, the housing data are assumed to represent conditions in the city for years 2011–2016.

To explore the relationship of each of the covariates with infant mortality and select the final variable coding, we first fit preliminary generalized linear negative binomial models, including one variable at a time as the predictor of infant mortality. We explored relationships across quartiles of the distributions of each individual variable, and subsequently collapsed variables across categories according to the relationships that we observed. We evaluated prediction by examining AIC statistics, as well as the magnitude of the regression coefficients relative to their standard errors. Our final selection of coding was based on consideration of model parsimony and outcome prediction. In final models, the covariates were coded as follows: percent Black/non-Hispanic, $< 50\%$ vs $\geq 50\%$; percent living below the poverty line dichotomized at the 25th percentile, $< 13\%$ vs $\geq 13\%$; population density per square mile dichotomized at the median, < 6920 vs ≥ 6920 ; and the housing indicator dichotomized at the median, $< 2.5\%$ of housing in the census tract with below average exterior condition vs $\geq 2.5\%$. Similarly, based on preliminary examination of dose-response relationships with infant mortality and consideration of AIC statistics in negative binomial models, we dichotomized the NDVI at the 75th percentile of the distribution (< 0.50 vs ≥ 0.50). As a sensitivity analysis, we reran analyses with NDVI parameterized as first- and second-order polynomial terms.

Results

After excluding 13 census tracts in which zero births occurred during the 5-year period, 371 remained in the analysis (Table 1). Across the 371 census tracts, there were 113,610 births and 963 infant deaths in total in years 2010–2014. The mean number of births and deaths, across census tracts, was 295.9 (standard deviation, SD 166.5) and 2.5 (SD 2.4), respectively. The mean infant mortality rate across census tracts was 8.2 per 1000 births (SD 7.1); this was higher than the US infant mortality rate in year 2014 (5.8 per 1000) [37]. Infant mortality rates varied vastly across census tracts in Philadelphia—ranging from 0 to 49.5 per 1000 births. The mean percentage of houses with a below average exterior condition was 5.2 (SD 7.0). Mean percentages of residents living below the poverty line and non-Hispanic Black were 26.5 (SD 15.8) and 42.9 (SD 35.4), respectively. Based on data from the US American Community Survey for years (2010–2014) [52], these percentages were higher compared to those for the entire US, where proportions living below the poverty line and non-Hispanic Black were 15.6 and 12.2, respectively.

The average median NDVI value was 0.41 (SD 0.14). Figure 1 shows great spatial variability in greenness across the city. To demonstrate links between the NDVI and characteristics of the urban landscape, Fig. 1 also shows the following city landmarks: (1) Philadelphia's International Airport, (2) Philadelphia's City Hall, a large, municipal building located in the center of the city's business district, (3) Bartram's Garden [55], a 45-acre landmark and garden operated in cooperation with Philadelphia Parks and Recreation department, and (4) Wissahickon Valley Park trail, an 8.5-mile greenway, that is, used for biking, horseback riding, walking, and other outdoor activities [56]. The figure shows that the census tracts with Bartram's Garden and the Wissahickon Valley Park trail have the highest NDVI values, whereas the lowest NDVI values are in the census tracts in the central business district.

In unadjusted models, the rate of infant mortality was 36% higher in less green census tracts (95% CI 1.08–1.74) (Table 2). After adjusting for poverty, race/ethnicity, housing quality, and population density, the rate of infant mortality was 27% higher in less green compared to more green tracts (95% CI 1.02–1.59). Estimates of the variance of spatial and non-spatial random effects are also given in Table 2. After adjusting

Table 1 Descriptive statistics for 371 census tracts in Philadelphia, PA, contributing to the analysis

	Mean (standard deviation)	Median	Range	IQR
Births (count)	295.9 (166.5)	277.5	0–923.0	197.3
Infant deaths (count)	2.5 (2.4)	2.0	0–14.0	3
Infant mortality rate, per 1000 births	8.2 (7.1)	7.0	0–49.5	9.1
Median NDVI, year 2012	0.4 (0.1)	0.4	0.1–0.8	0.2
% Living below poverty line	26.5 (15.8)	23.0	0–80.3	23.2
% Non-Hispanic Black	42.9 (35.4)	33.1	0–99.7	72.5
Population density, per square kilometer	7611.3 (4362.6)	6932.2	0.3–26,022.2	5660.7
Percentage of houses with below average exterior condition	5.2 (7.0)	2.6	0–41.5	6.8

for poverty, race/ethnicity, housing quality, and population density, the variance of the spatial random effects decreased dramatically, from 0.24 (95% CI 0.09–0.48) to 0.04 (95% CI 0.01–0.17), suggesting that these covariates help explain the spatial variability in infant mortality rates across the city.

To derive a quantitative estimate of the importance of spatial structure in our analysis, we computed the proportion of total variability in the random effects (i.e., the variance of the spatial random effects plus the variance of

the non-spatial random effects) attributable to the spatial random effects. In the adjusted model, of the variability not explained by our covariates, the spatial structure explained 76% (95% CI 18%–97%) of the total variability (Table 2). A map of the predicted rates of infant mortality within each census tract, based on the fully adjusted model, is given in Fig. 2. The map illustrates spatial patterning of the predicted infant mortality rates.

We did not observe evidence of effect modification by any of the variables we investigated

Fig. 1 Median greenness in each Philadelphia census tract quantified using satellite images of the normalized difference vegetation index (NDVI) from year 2012

Table 2 Rate ratios and 95% credible interval estimates of associations of infant mortality with greenness quantified as the median normalized difference vegetation index for the census tract in year 2012*

	Rate ratio (95% CI)	Variance of the spatial random effects τ^2 (95% CI)	Variance of the non-spatial random effects σ^2 (95% CI)	Ratio of variance parameters $\sigma^2/\sigma^2+\tau^2$ (95% CI)
Unadjusted	1.36 (1.08–1.74)	0.24 (0.09–0.48)	0.01 (0.00–0.05)	0.96 (0.75–0.99)
Adjusted	1.27 (1.02–1.59)	0.04 (0.01–0.17)	0.01 (0.00–0.06)	0.76 (0.18–0.97)
Modifiers				
% Living below the poverty line		0.03 (0.01–0.15)	0.01 (0.00–0.06)	0.72 (0.16–0.96)
Poorer	1.33 (1.03–1.74)			
Wealthier	1.27 (1.01–1.59)			
% Black/non-Hispanic		0.03 (0.00–0.18)	0.01 (0.00–0.06)	0.74 (0.10–0.96)
< 50% Black	1.20 (0.89–1.65)			
≥ 50% Black	1.39 (1.02–1.84)			
Housing quality		0.04 (0.01–0.18)	0.01 (0.00–0.06)	0.76 (0.20–0.97)
Lower quality housing	1.24 (0.94–1.65)			
Higher quality housing	1.31 (0.95–1.79)			
Population density		0.02 (0.00–0.17)	0.01 (0.00–0.06)	0.70 (0.13–0.97)
Lower	1.22 (0.96–1.56)			
Higher	1.43 (0.94–2.51)			

*All adjusted and stratified models are adjusted for census tract level estimates of percentages living below the poverty line (< 13% vs ≥ 13%), percentage of black/non-Hispanic (< 50% vs ≥ 50%), percentage of housing with below quality exterior condition (< 2.6% vs ≥ 2.6%), and population density (≤ 6920.2 vs > 6920.2)

(Table 2). Results from sensitivity analyses in which the NDVI was modeled using first and second order linear terms confirmed those from models in which the NDVI was dichotomized at the 75th percentile (data not shown).

Discussion

After adjusting for census tract-level poverty, racial/ethnic composition, exterior housing quality, and population density, and accounting for spatial autocorrelation, we found that higher greenness was associated with lower rates of infant mortality. These results contribute to emerging evidence that urban greenness is a health promoting environmental asset.

The mechanisms by which greenness protects against infant mortality remain unclear, but could be as diverse as buffering harmful hazards such as air pollution [9, 27], heat [29], noise [28], or promoting social cohesion [32]. In Philadelphia, urban greening of vacant lots has been shown to be associated improved mental health outcomes [57], improved perceptions of safety [58], increased use of outdoor spaces for socializing [58],

and reduced rates of crime [58]. Also in an experimental, neighborhood walking trial study in Philadelphia, compared to having a view of a non-greened vacant lot, having a view of a greened vacant lot was associated with lower heart rate [59], which the investigators used as a physiological marker of stress response. Given strong evidence that maternal anxiety and depression increase the risk of preterm birth [60, 61], and that preterm birth is associated with increased risk of infant mortality [26], it is possible that the association between greenness and infant mortality is mediated by maternal stress.

Our findings are consistent with results from a small body of previous research on associations of greenspace with infant mortality and birth outcomes. In Lyon, France [21], greenness levels partially explained spatial clusters of infant mortality. A larger body of literature suggests that greenness protects against poor pregnancy outcomes, including low birth weight, preterm birth/gestational age, preeclampsia, and gestational diabetes [62]. For example, Casey et al. found that, in Pennsylvania communities, higher densities of greenness were associated with lower rates of preterm birth and small for gestational age birth [63]; the magnitude of the

Fig. 2 Predicted infant mortality rates in each Philadelphia census tract for years 2010–2014, based on Bayesian spatial areal unit, conditional autoregressive models that included the following covariates: normalized difference vegetation index (NDVI, median value in year 2012), percent non-Hispanic Black, percent living below the poverty line, an indicator of housing quality, and population density

observed effects was similar to the effect estimates we observed (protective effects ranging from 22 to 27%).

Contrary to expectations, we did not observe strong evidence of effect modification by any of the covariates that we explored, including percent of non-Hispanic Black and percent of living below the poverty line. We expected that associations between greenspace and infant mortality would be more substantial in poorer tracts, and in tracts with higher percentages of non-Hispanic Black residents, because some of the mechanisms by which greenspace protects against infant mortality might be more important in these areas. For example, the heat-buffering properties of greenspace might be more important in poorer census tracts, where residents might have less access to other heat adaptative strategies (e.g., air condition). Rather, our results suggested that the positive impacts of greenspace are homogenous across areas. This is contradictory to findings from some previous studies, which have found evidence of greater benefits of greenspace in lower socioeconomic position areas [64]. Other studies, however, have found results more similar to ours [65], suggesting homogeneity of the effect of greenspace.

An important contribution of our analysis is our focus on mortality among infants. Infants are a particularly vulnerable subpopulation, and rates of mortality are often considered to be a powerful indicator of population health and well-being [15]. An advantage of focusing on infants is that this subpopulation is more likely than others to stay close to home in their first year of life. Therefore, the exposure estimates in this study are less subject to misclassification due to movement patterns (e.g., adults who spend a lot of time away from their home—at work, for example). In addition, we believe Philadelphia, PA, is an important setting for this analysis. In particular, the city is characterized by high rates of infant mortality, vast racial disparities, and immense spatial variability in rates of infant mortality [36]. Another strength of this work was the use of the NDVI to quantify greenness. This index represents overall greenness, and it takes into account all types of vegetation, including trees, grass, shrubs, and green roofing. The NDVI is also an objective measure of greenness, since it is based on images taken from satellites. Finally, a methodological strength of this analysis is the use of Bayesian models. Not only do these models

leverage the spatial structure inherent to the data to address the instability of rates based on small counts, but also an investigation of the spatial random effects themselves may provide insight into important predictors excluded from our analysis; we identify this as an area for future research.

Despite these strengths, we acknowledge several limitations. Even though we adjusted models for area-level indicators of sociodemographics, population density, and housing quality, it is possible that our results are biased due to residual confounding. Second, this was an ecologic analysis. It is possible that the census tract level estimates did not accurately represent individual infant exposures. This may not represent a great concern in Philadelphia, where census tracts are small and very densely populated. The average size of a census tract is less than 1 km² (0.88 km²), and the average population density is 17,520/km². Considering how densely populated the tracts are, individual-level exposures within census tracts may be relatively uniform. A third limitation is the cross-sectional nature of this analysis. It is possible that the address recorded at the time of the infants' death was not the residential location most reflective of the infant's or mothers' relevant greenness exposure. Because of the short time frame between pregnancy, birth and infant mortality, however, this concern may be less relevant as compared to analyses of greenspace impacts on other health outcomes. To accommodate potential problems related to sparseness in the numbers of infant deaths, we also combined several years of data on infant mortality. Such an approach has been taken in previous analyses of infant mortality [42]. Aggregating counts across years precluded the ability to observe any temporal patterns. Nevertheless, our focus here was on spatial, rather than temporal variability, and there were little differences in the median NDVI across years. Further, the years aggregated were sufficiently close that major changes in the spatial variability would not have occurred. Finally, because we only had aggregated counts of infant deaths for the entirety of a year and did not have information on the date of or age at death, we were unable to investigate relevant time windows of exposure. This is an area for future research.

This is one of the first analyses to document an association between greenspace and infant mortality. Thus, this work represents an important contribution to the growing literature that shows that urban greenness may improve health. Greening is an important and relatively easily implementable strategy to promote health

in our rapidly urbanizing world. Future work is needed to investigate the potential differential impacts of different types of greenspace on infant mortality, and to identify the mechanisms that contribute to these relationships.

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