Distribution Agreement

Greenspace and Mortality in Metropolitan Atlanta, Georgia

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Environmental Health and Epidemiology

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B.S., Davidson College, 2014

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An abstract of
A thesis submitted to the Faculty of the
Rollins School of Public Health of Emory University
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Abstract

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Greenspace has been shown to have salutogenic effects on physical and mental health in observational and experimental studies. However, the pathways through which public and private greenspace influence health may differ. This study investigates the relationship between public and private greenspace and mortality in the 20-county Metropolitan Atlanta region. Generalized estimating equations with a negative binomial distribution and a log link function were used to model the association between counts of deaths at the census tract level (stratified by age, sex, race and ethnicity and standardized by population size) and the percentage of that census tract covered by either total greenspace or public greenspace. Strata with 1-4 deaths were censored to protect confidentiality. Multiple imputations were used to account for censored data. When controlling for relevant census-tract level confounders, a marginally insignificant association was observed between percent greenspace coverage and mortality rate (IRR=0.97 per 10 percentage point increase in greenspace, 95% CI: 0.94, 1.00) and a marginally significant trend of decreasing IRR with increasing quintile of greenspace exposure (p=0.03). No association was detected between amount of public greenspace and mortality rates. Greenspace may be a tool for regional planners to positively influence population health. Future studies should examine the particular association between public greenspace and population health to inform planning practice and public policy.

Mortality and Greenspace in Metropolitan Atlanta

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Introduction

The past several decades have seen increasing research surrounding the importance of constructed and natural spaces in influencing public health (Frumkin, 2003; Northridge, Sclar, & Biswas, 2003; van den Berg et al., 2015). Researchers and policy makers increasingly recognize potential to use the built environment as a tool for health promotion and reduction of health inequalities (Mitchell & Popham, 2008; Northridge et al., 2003). Vegetated land ("greenspace") is one of the many features of physical environments that have been linked to health.

Studies have found an inverse association between mortality rate and amount of greenspace in a neighborhood or buffer (James, Hart, Banay, & Laden, 2016; Mitchell, Astell-Burt, & Richardson, 2011; Mitchell & Popham, 2008; Xu, Ren, Yuan, Nichol, & Goggins, 2017). This association is likely mediated through both improved mental and physical health (Hartig, Mitchell, Vries, & Frumkin, 2014; James, Banay, Hart, & Laden, 2015).

Defining greenspace

Studies on the connection between greenspace and health often do not precisely define what the term "greenspace" means. Across disciplines, greenspace always refers to some kind of land use involving vegetation, but whether that only includes large swaths of undeveloped land or if tree-lined streets contribute to greenspace may vary depending on the study (Taylor & Hochuli, 2017). Definitions of greenspace may also be influenced by what can be measured, especially in large-scale studies, rather than what is most likely causally connected to health. The lack of unified definition is further complicated by the fact that different types of greenspace may have different causal pathways to health (Figure 1). The present study attempts to operationalize two definitions of greenspace. Greenspace in general refers to any pervious, vegetated surface including small areas of greenspace such as tree-lined paths, lawns, garden all the way to parks, cropland and forests. "Public greenspace", on the other hand, is a subset of greenspace that only includes continuous vegetated land open to the general public for use including local, state and national parks, as well as other areas designated for special uses such as cemeteries.

Measuring greenspace

Exposure to greenspace can be measured in a variety of ways. National studies measuring the association between greenspace and health often use satellite imagery to calculate the mean Normalized Difference Vegetation Index (NDVI) of a given area as the measure of residential greenspace exposure (Gascon et al., 2015; James et al., 2015; James et al., 2016). The NDVI estimates vegetative density based on red and near-infrared light reflected from Earth's surface. Mean NDVI is a straightforward measurement of how green an area is, but it does not control for factors such as whether a green area is publicly accessible or sufficiently large. Large studies may also use national land cover datasets to measure the extent of greenspace (Gascon et al., 2015; James et al., 2015; Maas, Verheij, Groenewegen, De Vries, & Spreeuwenberg, 2006; Richardson et al., 2012). These national datasets can provide researchers with the ability to control for some factors that might affect greenspace use such as the greenspace type (agriculture, park land, forest ect.) and extent (Hartig et al., 2014; Maas et al., 2006; Wheeler et al., 2015). The quality and resolution of these national datasets vary from country to country. National datasets usually rely at least partially on satellite imagery.

NDVI and national land classification systems lend themselves towards classifying the amount of greenness or green land uses within a given area. That area is usually expressed as a buffer of some distance surrounding the subjects' homes (Bos, van der Meulen, Wichers, & Jeronimus, 2016; Browning & Lee, 2017; Feng & Astell-Burt, 2017; Maas, van Dillen, Verheij, & Groenewegen, 2009; Maas, Verheij, Spreeuwenberg, & Groenewegen, 2008; Orban, Sutcliffe, Dragano, Jöckel, & Moebus, 2017; Pereira et al., 2012) or as a percentage of land that is greenspace within a neighborhood or census boundary

(Astell-Burt, Mitchell, & Hartig, 2014; de Vries, Robert, Peter, & Peter, 2003; Mitchell et al., 2011; Mitchell & Popham, 2008; Richardson, Pearce, Mitchell, & Kingham, 2013; Roe et al., 2013; Wheeler et al., 2015; Xu et al., 2017).

In spite of the fact that the majority of research on greenspace and health uses some measure of quantity of greenspace as the exposure metric, it is probable that not all greenspace has the same relationship with health. The intuitive assumption that not all greenspace is equal is supported by research finding that perceptions of attractiveness and usability of greenspace are significantly associated with the likelihood that people use the space and with positive psychological health outcomes (Carter & Horwitz, 2014; Feng & Astell-Burt, 2017). Greenspace size, amenities, attractiveness and equitable access are all likely important mediators in the relationship between greenspace and health (Carter & Horwitz, 2014; Lachowycz & Jones, 2013). Self-reported quality of greenspace is limited in that it may be a result of both intrinsic characteristics of the interviewee as well as extrinsic characteristics of the space. It also does not necessarily inform which specific characteristics of greenspace make a space more or less likely to have health benefits. Objective attractiveness, access and amenities are extremely difficult to measure, and therefore rarely included as measurements of exposure in large observational studies. Measurements of greenspace exposure other than total quantity will often use location-specific data on parks, and measure exposure as distance to, amount of or size of parks in a neighborhood (Chaix et al., 2014; Hillsdon, Panter, Foster, & Jones, 2006; Sallis et al., 2016).

Greenspace, Well-Being and Mental Health

Natural environments may offer psychologically restorative benefits through increased feelings of well-being (Bowler, Buyung-Ali, Knight, & Pullin, 2010). The connection between greenspace and well-being was initially established in studies that measured responses to controlled exposures to nature. One of the first scientific inquiries into this connection showed that patients with views of a natural setting from their hospital bed had shorter recovery times than those in rooms with buildings facing a brick wall (Ulrich, 1984). Another study showed that study subjects who viewed slides of natural environments had healthier markers of psychological stress (measured primarily through questionnaires) than subjects who viewed slides of urban environments (Ulrich et al., 1991)

More recently, observational studies have attempted to investigate whether these effects observed from controlled exposure to greenspace persist under conditions of long term exposure in the living environment. Encouragingly, observational studies examining stress levels have been able to confirm the findings of early experimental studies using biomarkers such as cortisol rather than questionnaires as markers of psychological stress (Honold, Lakes, Beyer, & van der Meer, 2015; Roe et al., 2013).

Greenspace at the neighborhood level has been shown to be associated with increased social cohesion and social capital and decreased social isolation (de Vries, van Dillen, Groenewegen, & Spreeuwenberg, 2013; Maas et al., 2009; Orban et al., 2017). Reducing stress and increasing social cohesion may be mechanistic pathways through which greenspace can improve mental health (Hartig et al., 2014; James et al., 2015).

Observational studies have demonstrated that the quality and quantity of greenspace surrounding residences are positively associated with mental health measured a variety of ways including scales measuring depression and anxiety, measurements of cognitive dysfunction, self-rated mental health and self-rated general health or wellbeing (Alcock, White, Wheeler, Fleming, & Depledge, 2014; Astell-Burt et al., 2014; Bos et al., 2016; Carter & Horwitz, 2014; de Vries et al., 2003; Feng & Astell-Burt, 2017; Maas et al., 2006; Orban et al., 2017; Wheeler et al., 2015; Wu et al., 2017). The studies demonstrating this association are cross sectional or have a measure of greenspace taken at one point in time, with the notable exception of a study that showed improved mental health for people relocating from neighborhoods with less greenspace to neighborhoods with more greenspace (Alcock et al., 2014). In several studies, either the whole cohort or one stratum of the cohort exhibited an increasing, positive association between the measurement of perception of health or mental health up to a moderate amount of greenspace, beyond which the association either shrunk or did not change (Astell-Burt et al., 2014; Feng & Astell-Burt, 2017; Richardson et al., 2012; Wu et al., 2017). Subpopulations identified in different studies as having an exclusive or stronger positive association between greenspace and mental or general health included the elderly (Bos et al., 2016; Maas et al., 2006), youth (Maas et al., 2006), urban populations (Maas et al., 2006; Wheeler et al., 2015), females (Bos et al., 2016) and those of lower socioeconomic status (Maas et al., 2006; Wheeler et al., 2015). Recent systematic reviews concluded there is limited evidence for a positive association between quantity of greenspace surrounding residence and mental health in adults, insufficient evidence for children and strong evidence for a positive association between greenspace quantity and perceived mental health (Gascon et al., 2015; van den Berg et al., 2015).

Greenspace and Physical Health

Greenspace may also influence health through encouraging physical activity. In a sample of over 7000 participants in Paris, the amount of surface covered by public green or open space was significantly associated with higher odds of recreational walking (Chaix et al., 2014). The number of parks in a 0.5 km and 1 km distances was also positively associated with physical activity in a sample of approximately 7000 participants spanning 14 cities in 10 different countries (Sallis et al., 2016). Children in communities in California were more likely to be physically active as measured by an accelerometer in areas with higher NDVI (Almanza, Jerrett, Dunton, Seto, & Pentz, 2012). Several studies have found no relationship between amount of residential or neighborhood greenspace and physical activity (Hillsdon et al., 2006; Maas et al., 2008). However, the weight of evidence still points towards a positive association between the amount of greenspace or parks surrounding a person's residence and the odds of physical activity (James et al., 2015; Kaczynski & Henderson, 2007). In a mediation analysis of the relationship between greenspace and general health, two studies have found that the association between greenspace and factors related to mental health is independent of and larger than the association between greenspace and physical activity (James et al., 2016; Richardson et al., 2013). This finding was supported by Maas et al.'s mediation analyses of one data set in two separate studies, which found a significant relationship between greenspace and the number of social contacts, but not greenspace and increased walking or cycling (Maas et al., 2009; Maas et al., 2008).

Greenspace has been associated with a number of cardiovascular outcomes (Pereira et al., 2012) which may be at least partially mediated through increased physical activity, though stress reduction may also be a contributing route cause to these physical improvements (James et al., 2015) .

Greenspace and Mortality

A recent systematic review found strong evidence for an inverse association between greenspace and mortality (van den Berg et al., 2015). Perhaps the most convincing evidence that greenspace exposure can delay mortality comes from a survival analysis of participants in the Nurses' Health Study (James et al., 2016). The study measured both current exposure and cumulative exposure to greenness over the course of eight years of follow up using the mean NDVI values within a 250-meter buffer and a 1250 meter buffer of place of residence. All measurements of greenness exposure showed a significant trend of decreasing hazard of mortality with increasing NDVI. The general finding of lower mortality rate associated with greater quantity of greenspace immediately surrounding the residence is supported in ecological and cross-sectional studies (Coutts, Horner, & Chapin, 2010; Mitchell et al., 2011; Mitchell & Popham, 2008; Xu et al., 2017). However, one study found greater rates of mortality in greener cities (Richardson et al., 2012). Controlling for the level of auto-dependence of the city reduced this correlation, but the association remained significant (Richardson et al., 2012).

Studies on mortality and greenspace almost exclusively use a measure of the quantity of greenspace either surrounding the home within a distance buffer or within a residential unit such as a census tract (Coutts et al., 2010; James et al., 2015; Mitchell et al., 2011; Mitchell & Popham, 2008; Xu et al., 2017). Quantity of greenspace is operationalized either as mean NDVI (James et al., 2016; Xu et al., 2017) or percentage coverage greenspace as defined by national land cover dataset (Mitchell et al., 2011; Mitchell & Popham, 2008) within the relevant buffer or neighborhood division. The exception is the ecological, county-level analysis of Coutts et al. (2010), which uses a state dataset that only includes publicly accessible land as greenspace. The analysis found a significant reduction in all-cause mortality and cardiovascular mortality associated with increasing green space only when the amount of greenspace within the county was weighted by the number of people that had access to that greenspace. No association was found between mortality and the crude amount of greenspace or average distance to greenspace within a county (Coutts et al., 2010). Their finding illustrates that the distribution, rather than just the amount of greenspace can be important to health.

Public vs Private Greenspace

Public and private greenspaces likely serve different functions in terms of health and cannot be assumed to be simple substitutions of each other (Coolen & Meesters, 2012). Public greenspaces may be more suitable for social interaction and physical activity, whereas greenspaces associated with private residences are likely more suitable for providing relaxation, escape and restoration (Coolen & Meesters, 2012). Hartig (2014) suggests the four pathways through which greenspace can improve health are reduction of air pollution, reduction of stress, increased physical activity and increased social contacts. Those pathways may depend on passive exposure to greenspace, active use of greenspace or both (Figure 1). Public spaces are likely to be more important for health outcomes on the active use pathways, whereas both private spaces and public spaces near residences can influence the passive exposure pathways. Although this assumption about the differential importance of different types of greenspace in different health outcomes is not explicitly expressed in most observational studies, itis implicit in the ways greenspace is measured in studies of different health outcomes. When the outcome of interest is physical activity, the amount of parkland area, distance to the nearest park or size of the nearest park are often used as exposure variables (Chaix et al., 2014; Hillsdon et al., 2006; Sallis et al., 2016). In contrast, when the outcome is related to mental health, a measurement of the total amount of greenspace within a census region or distance from a participant's residence is typically used as the exposure (Alcock et al., 2014; Astell-Burt et al., 2014; Bos et al., 2016; Roe et al., 2013). Previous studies of the relationship between greenspace and mortality have also used measurements of the amount of greenspace, which typically do not differentiate between the role private and public spaces may play in the relationship (James et al., 2016; Mitchell et al., 2011; Mitchell & Popham, 2008; Richardson et al., 2012; Xu et al., 2017).

Greenspace and health: non-linear relationships

Models estimating the relationship between the quantity of greenspace and some health outcomes often use continuous measures of greenspace, which preclude the detection of non-linear relationships. In observational studies that examined the dose-response relationship between the quantity of greenspace and a health outcome, some have demonstrated a linear dose-response in at least one subpopulation (Astell-Burt et al., 2014; James et al., 2015; Mitchell et al., 2011). However, it is not uncommon for observational studies to find non-linear associations between greenspace and health, with health benefits plateauing (Astell-Burt et al., 2014; Feng & Astell-Burt, 2017; E. A. Richardson et al., 2013; Wu et al., 2017)or apparently (though not statistically significantly) declining (Astell-Burt et al., 2014; Wu et al., 2017) beyond moderate amounts of greenspace coverage. Wu et al. (2017) suggested that the parabolic relationship in their study population between cognitive impairment and living in an area with more natural environment availability could be because too little or too much environmental stimulus are both harmful to cognitive function. A similar causal argument was not made to explain findings that British women living in moderate levels of greenspace had the highest self-reported health, Australian children in areas with moderate percentage greenspace coverage had the lowest Total Difficulties Score on the Strength and Difficulties Questionnaire, or that the association between greenspace coverage and reduced mortality due to cardiovascular disease plateaued beyond 15% greenspace coverage (Astell-Burt et al., 2014; Feng & Astell-Burt, 2017; E. A. Richardson et al., 2013).

Another explanation is that there is an unmeasured cost to living in the greenest areas for certain segments of the population. De Vries (2003) found a stronger protective estimated effect of greenspace on number of symptoms reported in housewives and in the elderly. Similarly, Bos et al. (2016) found a positive association between greenspace and health in women and in certain age groups, but a negative effect in the 45-54 age group.

Working age populations may not have the same opportunity to benefit from residential greenspace. Living in green areas may also correspond with longer commutes, which could reduce exposure to residential greenspace. Longer commutes are also associated with poorer psychological health outcomes and higher stress (Evans & Wener, 2006; Hilbrecht, Smale, & Mock, 2014; Künn-Nelen, 2016). Richardson et al.'s (2012) finding that the most green cities in the United States have the highest mortality rate circumstantially supports the idea that while greenspace itself may be beneficial, populations in greener cities could be coping with negative health effects related to urban sprawl, including the effects of increased commuting.

The present analysis examines the relationship between greenspace and mortality rates at the census tract level. This is the first analysis of the association between greenspace and mortality to measure effect of public and private greenspaces separately, and the first place-specific analysis of greenspace and mortality in a sprawling metropolitan area in the southeast United States, which has a much different distribution of greenspace than existing place specific analyses of this relationship from Europe and China.

Methods

Study site description

The study site is the 20-county area defined by the Atlanta Regional Commission (ARC, a regional planning agency) as the Metropolitan Atlanta area (Figure 2). The Atlanta area is a sprawling, unevenly developed region that covers a wide range of development density. The population density ranges from over 20,000 people per square mile near downtown Atlanta to less than 70 people per square mile in several exurban census tracts.

Mortality data

The Georgia Department of Public Health provided counts of deaths of people aged 20 or older who died from any cause between January 1, 2012 and December 31, 2016 for each of Metro Atlanta's 943 census tracts, stratified on several covariates. The data were de-identified, and collection of these data was approved by Emory University's Internal Review Board. Any stratum within a census tract that included a count of 1 to 4 deaths was censored to protect confidentiality. There was therefore a trade-off between stratifying on more covariates, which would provide more specific information on who is dying and having to censor a larger portion of the data set. Two datasets were therefore used for the analysis, one stratifying on all categories of interest including sex, five age categories, race (white, black and other) and ethnicity with 14.7% of the deaths censored, and one stratified on sex and two age categories (younger than 65 vs 65 and older), which resulted in a minimally censored dataset (0.2% of deaths were censored). Models fit to the minimally censored data set were suspected to have strong residual confounding due to age (Appendix). The highly stratified dataset was therefore served as the primary dataset from which to draw conclusions.

Values were imputed for censored deaths using integers randomly selected from a log normal distribution (reflecting the overall distribution of the count of deaths) between 1 and 4. The mean rate ratio for each quintile was computed from five imputations of missing values. Confidence intervals for the mean result of the imputations were calculating according to Rubin's Rules (Rubin, 1987).

Greenspace data

Data on total greenspace came from the 2011 National Land Cover Database (NLCD). The NLCD classifies land cover into 20 different categories across the entire United States at 30-m spatial resolution using satellite imagery from the Landsat 5 Thematic Mapper. The Multi-Resolution Land Characteristics Consortium (MRLC), a cross- agency federal effort including the U.S. Geological Survey, the National Oceanic and Atmospheric Administration and the U.S. Forest Service, performs the classification of the imagery. The area of each land cover type that was present was calculated for 943 census tracts and divided by the total area of the census tract using ArcGIS v. 10.5.1. Of the 15 land cover types present in metro Atlanta, 9 were considered 100% greenspace. Open water and barren land were not included in the calculation of greenspace. There are four categories that represent increasing development density: developed, open space where impervious surface represents less than 20% of total land cover, developed, low intensity where impervious surface represents 20-50% of land cover, developed, medium intensity developed where impervious surface accounts for 50-80% of land cover and developed high intensity where impervious surface accounts for 80-100% of land cover. Following the example of Richardson et al. (2012), any pixels classified within one of the developed categories was assumed to have the midpoint of impervious surface, and any non-impervious surface was assumed to be greenspace. For example, a pixel classified as medium intensity developed would be assumed to be 35% greenspace.

Data on public greenspace came from an inventory of greenspace in metro Atlanta maintained by the Atlanta Regional Commission, with input from county governments. The inventory was last updated and reviewed by all local county and city governments in 2016.

Population and data on potential confounders

Data on the population stratum-specific and census-tract level confounders came from 5-year 2012-2016 American Community Survey estimates from the U.S. Census Bureau. The American Community Survey is an annual survey that pulls from a stratified sample of every census bloc in the nation designed to provide estimates of population characteristics in years in between the decennial census. Although the survey is conducted annually, only multiyear estimates are available at the sub-county level in order to protect confidentiality of respondents and reduce variance. Estimates represent an average value of a given parameter over the five year period (U.S. Census Bureau, 2017).

The ACS provides population size estimates stratified on age, sex and ethnicity for non-Hispanic whites, but only provides estimates stratified on age and sex for other races. This presented a challenge for calculating population at risk in each stratum for African Americans and racial groups in the “other” category. The number of people in each age and sex stratum within these two racial groups were multiplied by the proportion of people in the relevant racial group who identified as Hispanic in that census tract to estimate the population at risk. In the median census tract, only 1% of Hispanics identified as black, and there were no counts of deaths greater than four in the study area among black Hispanics, nor any of the strata of Hispanics in the “other” racial category. The estimates of populations at risk that had the greatest margin of potential error were therefore in the strata with few people at risk.

Potential confounders were selected based on models from previous studies and a priori belief that the factor could influence mortality rate and had a geographical gradient that could induce a relationship with percent greenspace coverage. Census tract level variables evaluated as potential confounders include percent of the population with less than a high school education, percent with a bachelor's degree or higher, percent of population who is white only, percent African American only, percent who commute more than 30 minutes, percent who commute more than 60 minutes, percent of the census tract's working population in the labor force, median income, percent of the population living in poverty and urbanity which was operationalized as living in the two counties closest to the urban core (Fulton and DeKalb) vs living elsewhere. Variables representing the percentage of the population in each of the four age and sex strata within five age ranges for every census tract were also created due to concern that stratification on two age categories would not be sufficient to control for confounding due to age. All census tract variables as well as age and sex were also evaluated as potential effect modifiers because of the potential for a stronger protective effect of greenspace in low SES, urban and non-working populations.

Primary statistical analysis

Generalized estimating equations (GEEs) with a negative binomial distribution were used to estimate the effect of both private greenspace and public greenspace on mortality. GEEs were necessary because exposure and confounders were measured at the census tract level while the count of deaths was stratified on individual covariates. GEEs using the Poisson distribution were not selected because they were overdispersed (mean < variance). An exchangeable correlation structure was used because it produced the models with the smallest quasilikelihood under the independence model criterion (QIC). The residuals for models with different covariance structures were tested for spatial autocorrelation using an inverse-distance weighted Moran's I to determine if GEEs naïve to spatial structure could effectively control for spatial autocorrelation. Prior to adding imputed values, residuals of the fully adjusted model for all greenspace remained spatially autocorrelated (p=0.005) regardless of covariance structure, although the magnitude of the correlation was small (Moran's I=0.004). The residuals for the fully adjusted model examining percent greenspace were similarly correlated (Moran's I=0.02, $p<0.0001$). Spatial autocorrelation was significant in half of the models on imputed data, and the magnitude of autocorrelation remained small in all models (minimum Moran's I=0.0002 maximum Moran's I=0.005). Given the small magnitude of spatial autocorrelation in all models and the inconsistent statistical significance of Moran's I in imputed models, the potential for spatial autocorrelation to influence the results was considered small, and regression techniques to control for spatial autocorrelation were not employed. Exposure was classified into quintiles in order to detect potentially non-linear trends. Interaction terms were assessed via stepwise elimination and were included in the model if they were statistically significant according to the generalized score statistic.

Results

Descriptive statistics

There were 166,990 total deaths in the study area from 2012 to 2016. 24,618 (14.7%) of these deaths occurred in strata in census tracts for which data were censored and were therefore not included in the analysis. 929 (98.5%) of 943 census tracts had at least one uncensored stratum. Percentage greenspace coverage tended to be high in this verdant study area with a mean of 74.2% (SD 14.2%) greenspace coverage. Death rates exhibited modest spatial autocorrelation (Inverse Distance Weighted Moran's I=0.28 $p<0.0001$, Figure 4) and greenspace was highly spatially autocorrelated (IDW Moran's I=1.04 $p<0.001$, Figure 2).

The percent of the population commuting over 60 minutes, the percent of the population that is Caucasian and the percent over the age of 65 all had a modest, positive linear correlation with greenspace (r^2 ranged from 0.31-0.35). Variables associated with socioeconomic status had a consistent trend of higher SES from the first through the fourth quintile (as operationalized by greater median income, greater proportions of the population with more formal education and lower poverty rates), and lower or the same SES from quintile four to quintile five (Table 1). The geographic distribution of neighborhood SES variables followed the pattern shown in Figure 5, with higher SES areas north of the city, lower SES areas to the south and middle class areas in the outer exurban ring. Census tracts in quintile 5 are concentrated in the outer reaches of the study area (Figure 2). Public greenspace tended to have low percentage coverage within census tracts (Table 1, Figure 3).

In the highly stratified dataset, 14.7% of deaths and 65.8% of strata were censored (Table 2). Strata estimated to have no one or less than one person at risk during the five-year period were excluded from the main model, which included 28,082 strata (49.7%). 22,746 (81.0%) of the strata that had virtually no population at risk were strata that included people of Hispanic ethnicity.

Main model results

Interaction by sex (p=0.24) and interaction by age (p=0.07) were not statistically significant, and therefore not included in the model. Models on uncensored data only showed no statistically significant association between total greenspace coverage and mortality rate in any quintile of percentage greenspace coverage, with many estimates close to null (Table 3). The estimate of the association between continuous percent greenspace coverage and mortality rate was also insignificant (Table 3). For public greenspace, models restricted to uncensored observations found almost all quintiles had significantly greater rate ratios compared to the lowest quintile of public greenspace coverage for crude and fully adjusted models, but no there was no statistically significant positive, continuous trend in quartile results and the estimated associations between continuous percentage public greenspace and mortality rate was insignificant for both models.

Results from models combining multiple imputations of censored data indicated different associations than models restricted to uncensored data. The adjusted rate ratios comparing the mortality rate in each of the highest four quintiles of percent greenspace coverage vs the lowest quintile of greenspace coverage were all less than one, although only one comparison was statistically significant, and there was a significant trend of decreasing mortality rate ratio with increasing quintile of greenspace coverage (Table 4). Rate ratios comparing mortality rate in the highest four quintiles of percent coverage of public greenspace vs the lowest quintile were all at or above the null, but none were statically significant, and there was not a significant trend by quintile (Table 4).

Discussion

Greenspace and mortality

In this census-tract level study of mortality and greenspace in Metro Atlanta, a marginally significant trend of decreasing mortality rate with increasing quintiles of total greenspace coverage was observed, with a marginally insignificant inverse relationship between continuous percent greenspace coverage and mortality rate. No relationship was observed between percent public greenspace coverage and mortality rate.

The significant trend by quintiles of total greenspace is consistent with findings of most previous studies associating increased greenspace exposure to decreased mortality rate (Coutts et al., 2010; James et al., 2016; Mitchell et al., 2011; Mitchell & Popham, 2008). The null result in the linear association between total greenspace and mortality rate was not in line with the findings of a protective association in cross-sectional analyses with more detailed individual level data (James et al., 2016; Mitchell & Popham, 2008). Xu et al. (2017) assessed the relationship between average NDVI and mortality rate at a similar geographic unit (Tertiary Planning Unit) as this study in Hong Kong. Like this study, their analysis did not find a significant linear association between greenspace and all-cause mortality, but they did find greenspace was associated with a 11% decrease (95% CI: 3%-8%) in mortality from cardiovascular disease. The sample size of geographic areas (943 in the present study, 289 in Xu et al.) may limit study power and the limited control for individual level data opens the possibility of residual confounding.

These factors may make it difficult to detect the relatively small effect of greenspace on mortality, which has been measured as a 6%-12% effect size (James et al., 2016; Mitchell & Popham, 2008). The results of this study are contrary to Richardson et al.'s (2012) analysis of city-level greenness and mortality. This difference is likely driven by the Richardson et al.'s lack of ability to control for individual level factors, as well as regional factors associated with increased city level greenspace that can have a negative effect of health, such as automobile dependence. Notably, removal of control for commuting time reduced the strength of the association observed in the multiple imputation model for all greenspace (results not shown).

No existing studies on mortality differentiated between public and private greenspace, but the dataset used to estimate greenspace in the analysis conducted by Coutts et al. (2010) in Florida was restricted to public greenspace. Their analysis did not detect any significant association between the amount of greenspace in a county and the mortality rate, but mortality rate was associated with a complex measurement of greenspace accessibility which took into account average distance of census tracts from greenspace weighted by the population of each census tract. This present study also did not detect an association between amount of public greenspace and mortality rate. The percent coverage of public greenspace was less than 0.1% for all census tracts. Since public greenspace takes up a relatively small amount of the region, it is unlikely that public greenspace alone significantly influences the passive exposure of most of the population to greenspace in any census tract. It is therefore more likely to have health effects through the active use of greenspace pathway illustrated in Figure 1. Accessibility may be a more important measurement than the amount of public greenspace since accessibility can influence how many use the space. Accessibility was not measured in this study.

Results from the models restricted only to uncensored data were likely biased by the fact that more strata were censored in the lowest quintile of percentage greenspace coverage. Restricting on uncensored data therefore underestimated the mortality rate more in quintiles with lower greenspace coverage than those with higher greenspace coverage. This could have driven the insignificant findings for total greenspace coverage and the positive rate ratios in higher quintiles of public greenspace.

Limitations

One limitation to this study is that several important confounders were measured at the census tract level rather than the individual level. More individual level data would have provided the opportunity to control both for neighborhood-level variables using information collected at the census tract level and individual level characteristics such as income and education that can influence mortality. Data on confounders, and more importantly on the population at risk, were pulled from the American Community Survey, which is a stratified sample and therefore has error associated with its estimates.

The results of the models based on multiple imputations can be influenced by the assumption underlying the distribution of the missing values. A log-normal distribution was assumed because the uncensored count of deaths was distributed in a log-normal fashion. However, if this assumption is incorrect the results from the models presented here may be biased.

The estimated population at risk in non-white, Hispanic strata and in the "other" racial category likely had a high percentage error due to the lack of a precise estimate of those populations in the ACS. However, this was unlikely to influence the final result. The estimate of populations of non-Hispanic African Americans at risk was not heavily influenced by the subtraction of the proportion of Hispanic African Americans because there were zero Hispanic African Americans in most census tracts. A large percentage of Hispanic and other strata were not included in the models due to the estimated population at risk being less than one (Table 2). The total Hispanic and other population at risk was exactly the same as in the ACS, virtually all of these strata had zero deaths, and they represented a small proportion of the total population.

Another key limitation is that mortality data were not cause specific, making it difficult to speculate what the particular social or biological pathways are that could lead to the observed association between greenspace and health. Similarly, the crude measurement of amount of greenspace does not allow for any inference about the role different types of greenspace might have in the relationship between greenspace and health beyond examining the importance of publicly accessible greenspace. Measurements of both public and total greenspace were taken at one point in time and are probably not representative of cumulative exposure to greenspace over a lifetime, even assuming few residents move into or out of a given census tract. The model fit to these data did not consider spatial relationships and spatial autocorrelation was present, though the magnitude was small. Future analyses of these or similar data might attempt to fit models with both spatial covariance and covariance to account for repeated measures. Finally, as with any observational study of exposure to greenspace, self-selection bias could influence the observed association if healthier people are more inclined to live in green areas.

Conclusions

Even in a relatively verdant region in a metropolitan area with dispersed development, increased greenspace exposure is associated with reduced mortality rate. As the world's population becomes increasingly urban, planning cities and metropolitan areas that incorporate greenspace may improve population health. The health benefits of greenspace, however, must be weighed against the health consequences of urban sprawl and automobile dependence (Richardson et al., 2012). More research is needed about the particular relationship between public greenspace and health outcomes, as public greenspace is the easiest to influence from a policy and planning perspective. Public greenspace located in densely populated areas may be more important in areas with high population density (Coutts et al., 2010). Future studies might examine the influence of public greenspace quality and accessibility on population health.

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Tables and Figures

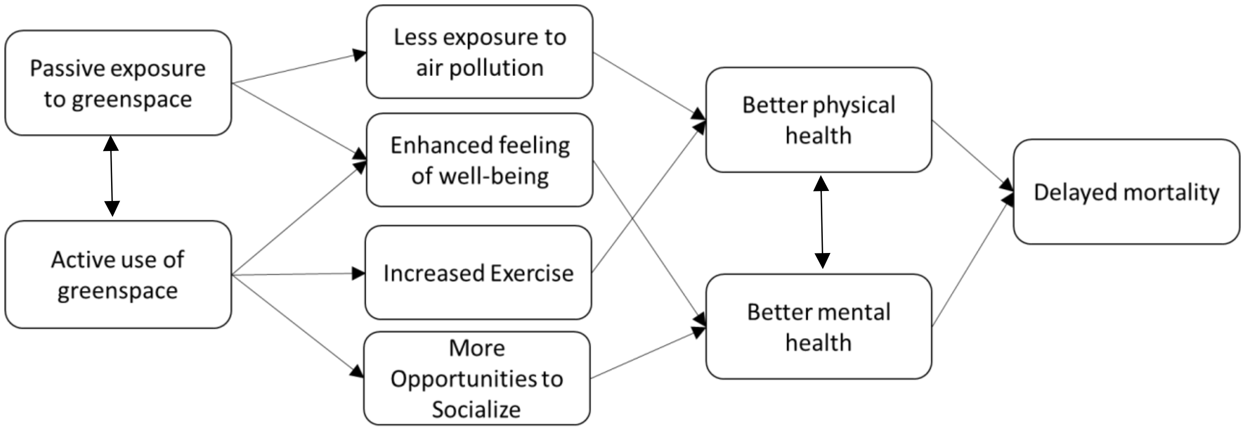

Figure 1. Pathways from exposure to greenspace to reduced mortality rate in a population. Active use of public parks may have separate pathways to improve health outcomes than passive exposure to green environments. Figure was informed by Hartig (2014).

Table 1. Metro Atlanta census tract characteristics by quintiles of percentage greenspace coverage.

	Mean	Quintiles of Greenspace				
		Q1	Q2	Q3	Q4	Q5
Number of census tract	943	198	186	188	188	183
Percent greenspace	74.2	53.0	69.1	76.0	82.5	91.8
Percent public greenspace x 10^{-4}	8.8	0	0.6	3.4	8.7	31.6
Thousands of person time contributed	20087	3317	3973	4208	4265	4326
Demographics						
Percent over 65	6.6	7.6	9.4	11.3	12.1	12.1
Percent male	52.5	50.4	48.4	47.8	48.1	49.2
Percent Caucasian	58.1	42.2	48.4	50.2	60.4	75.2
Percent African American	28.3	42.7	35.3	39.8	31.2	19.2
Socioeconomic Indicators						
Percent less than high school	9.0	14.3	12.2	9.2	8.6	12.3
Percent bachelor's or higher	57.9	42.7	43.1	47.4	45.7	33.6
Median Income (2016 US dollars)	72,755	45,766	58,502	67,708	74,774	62,806
Percent in Poverty	21.4	25.0	18.8	15.2	12.4	12.8
Percent of people age 16-65 currently employed	69.7	69.8	68.9	67.8	65.6	64.3
Commuting						
Percent Commute > 30 mins one way	35.7	39.7	46.4	49.7	49.8	50.3
Percent Commute > 60 mins one way	6.8	8.6	11.1	11.2	12.4	14.1

*census tracts with one or more strata censored

Table 2. Characteristics uncensored counts of deaths in Metro Atlanta census tracts stratified on five age categories, sex, three racial categories, and Hispanic vs non-Hispanic

	No of uncensored strata (% of strata)*	No of uncensored strata in model (% of strata in model)**	No of uncensored deaths (% of deaths uncensored)
Total	43,656 (77.2)	18,479 (65.8)	142,372 (85.3)
Quintile of greenspace exposure			
Q1 (lowest)	11,982 (75.6)	4934 (62.9)	21,368
Q2	8635 (19.7)	3785 (63.0)	24,819
Q3	7941 (77.4)	3469 (66.8)	26,747
Q4	7850 (79.8)	3281 (69.4)	28,774
Q5	7474 (80.9)	3010 (69.9)	32,367
Age			
20-29	9449 (83.2)	4117 (70.6)	905 (23.4)
30-44	8753 (77.1)	4363 (64.5)	4062 (46.9)
45-59	8971 (79.1)	4469 (69.1)	22,010 (83.2)
60-74	7903 (69.6)	2971 (51.3)	39,132 (82.9)
75+	8580 (77.1)	2559 (79.1)	76,203 (94.4)
Sex			
Male	21, 492 (76.0)	8805 (63.65)	70,692 (84.5)
Female	22,164 (78.4)	9674 (67.9)	71,680 (86.0)
Race			
White	13297 (70.47)	8975 (66.6)	103,392 (90.4)
Black	14047 (74.86)	4880 (56.8)	38,390 (79.5)
Other	16312 (86.3)	4624 (77.0)	590 (13.7)
Ethnicity			
Not Hispanic	17,976 (63.8)	13906 (89.0)	142,319 (87.1)
Hispanic	25,680 (90.5)	4593 (81.2)	53 (1.5)

*Strata with counts of deaths between 1 and 4 were censored

**Only strata with one or more people at risk during the 5-year period were included in the model

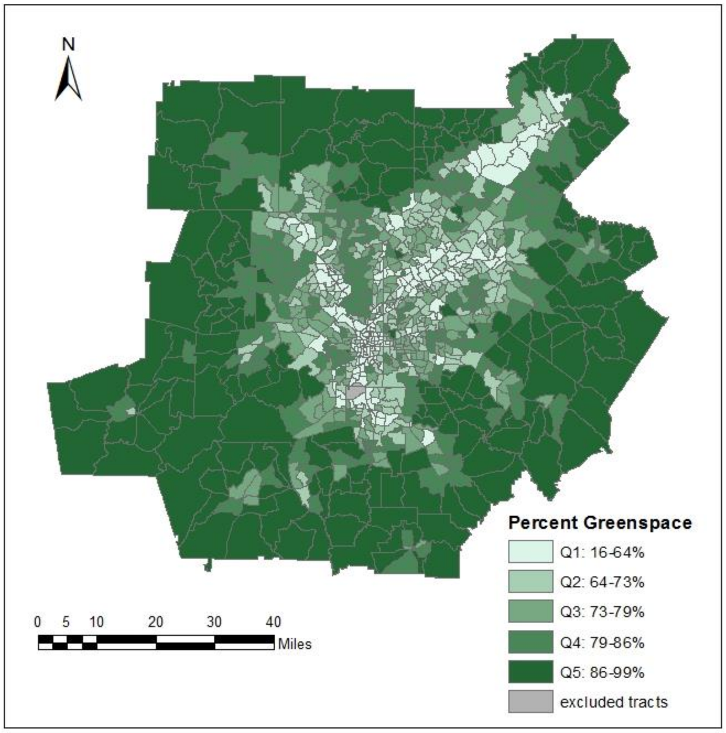

Figure 2. Census tracts in Metro Atlanta by quintiles of percentage greenspace coverage. Greenspace calculated from NLCD 2011.

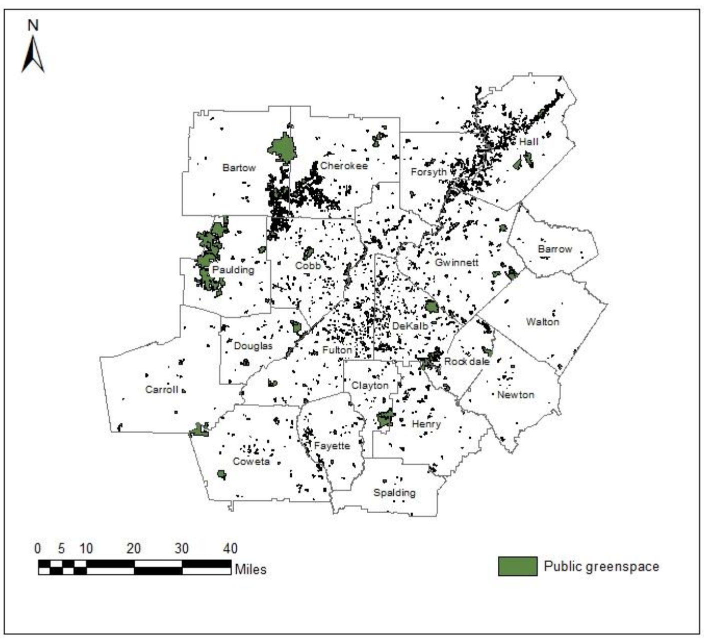

Figure 3. Public greenspace in Metro Atlanta, 2016.

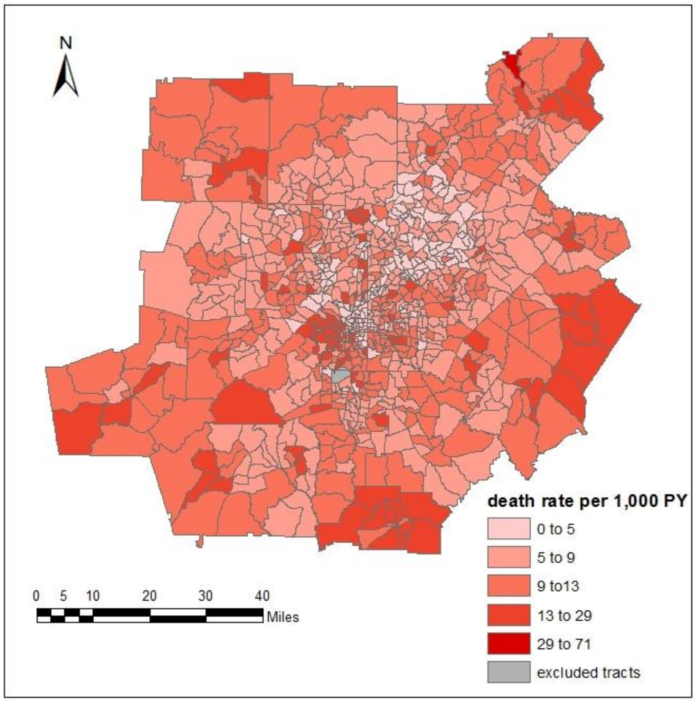

Figure 4. Death rate by census tract. Metro Atlanta, 2012-2016

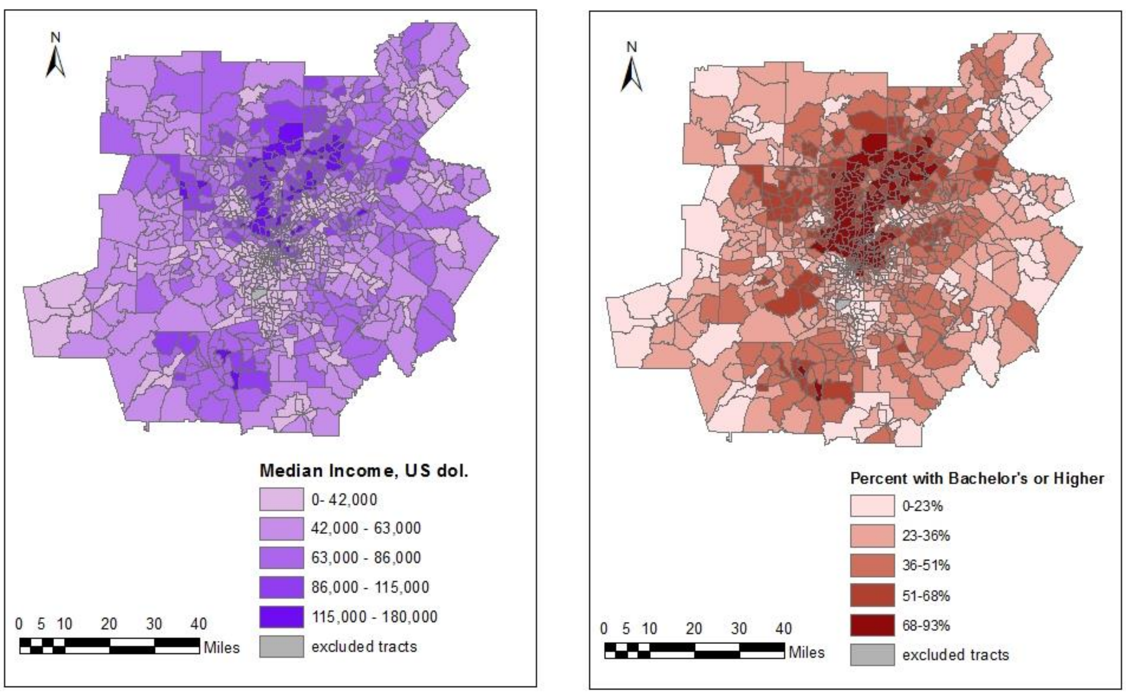

Figure 5. Median income (left) and percent of population with a bachelor's degree or higher (right). Metro Atlanta, Georgia 2012-2016. Distribution of SES-related variables generally follow the same pattern of high SES in the north side of Atlanta and inner suburbs, lower SES on the south side of Atlanta and southern suburbs, and middle SES areas in suburbs father from the urban core.

Table 3. Metro Atlanta mortality rate ratios and 95% confidence intervals of greenspace quintiles on highly stratified count dataset, uncensored values only*

	All Greenspace		Public Greenspace	
	Model 1a^ Adj. IRR (95% CI)	Model 1b^^ Adj. IRR (95%CI)	Model 2a^ Adj. IRR (95% CI)	Model 2b^^ Adj. IRR (95% CI)
Q1 (lowest)	1.00	1.00	1.00	1.00
Q2	0.93 (0.89-1.02)	0.98 (0.92-1.05)	**1.16** (1.06-1.26)	**1.11** (1.05-1.19)
Q3	0.93 (0.86-1.01)	0.99 (0.92-1.06)	**1.16** (1.05-1.20)	**1.10** (1.04-1.18)
Q4	0.93 (0.85-1.01)	1.00 (0.93-1.07)	**1.14** (1.06-1.20)	**1.13** (1.06-1.21)
Q5 (highest)	1.02 (0.94-1.10)	1.00 (0.93-1.10)	1.08 (0.99-1.18)	**1.06** (1.03-1.18)
p trend+	0.78	0.81	0.56	0.18
Continuous++	1.01 (0.98-1.03)	1.06 (0.93-1.21)	0.98 (0.88-1.09)	1.00 (0.89-1.07)

* death counts were stratified on five age classes, sex, race (white, black and other) and ethnicity (Hispanic vs not Hispanic)
^ model was adjusted for stratified variables only
^^model was adjusted for stratified variables as well as adjusted for percent of population in each census tract who is white, percent African American, percent with less than a high school education, percent with a Bachelor's degree or higher, and percent in poverty, median income, percent who commute greater than 30 minutes, percent who commute greater than 60 minutes, percent of the work force age population currently in the labor force, urbanity (1 if in Fulton/DeKalb, 0 if elsewhere)
+Significance of linear test for trend using ordinal rank for each quintile
++Per 10 percentage point (absolute) increase in all greenspace and 10 percent relative increase in public greenspace

Table 4. Metro Atlanta mortality rate ratios and 95% confidence intervals of greenspace quintiles on highly stratified count dataset, censored values imputed*

	All greenspace model^ Adj. IRR (95%CI)	Public greenspace model^ Adj. IRR (95% CI)
Q1 (lowest)	1.00	1.00
Q2	0.96 (0.87-1.06)	1.08 (0.97-1.19)
Q3	0.92 (0.83-1.03)	1.02 (0.92-1.12)
Q4	**0.87** (0.77-0.99)	1.00 (0.90-1.11)
Q5 (highest)	0.90 (0.78-1.04)	1.01 (0.92-1.12)
p trend+	**0.03**	0.68
	0.97 (0.94-1.00)	1.00 (0.97-1.02)

* death counts were stratified on five age classes, sex, race (white, black and other) and ethnicity (Hispanic vs not Hispanic)
^ model was adjusted for stratified variables only
^^model was adjusted for stratified variables as well as adjusted for percent of population in each census tract who is white, percent African American, percent with less than a high school education, percent with a Bachelor's degree or higher, and percent in poverty, median income, percent who commute greater than 30 minutes, percent who commute greater than 60 minutes, percent of the work force age population currently in the labor force, urbanity (1 if in Fulton/DeKalb, 0 if elsewhere)
+Significance of linear test for trend using ordinal rank for each quintile
++Per 10 percentage point (absolute) increase in all greenspace and per 10 percent relative in public greenspace

Appendix

The models below are based on the dataset stratified only on sex and two age categories. Given the results are positive and that the age distribution of census tracts tends to increase with greenspace (Table 1) it is likely that strong residual confounding due to age influenced these results.

Table 5. Metro Atlanta mortality rate ratios and 95% confidence intervals of greenspace quintiles, minimally stratified dataset

	All Greenspace		Public Greenspace	
	Model 1a* Adj. IRR (95% CI)	Model 1b** Adj. IRR (95%CI)	Model 2a* Adj. IRR (95% CI)	Model 2b** Adj. IRR (95% CI)
Q1	1.00	1.00	1.00	1.00
Q2	0.99 (0.92-1.06)	1.02 (0.96-1.06)	**1.10** (1.04-1.17)	**1.04** (1.00-1.09)
Q3	0.98 (0.91-1.05)	0.99 (0.94-1.04)	**1.12** (1.05-1.20)	**1.05** (1.01-1.10)
Q4	1.01 (0.94-1.08)	1.02 (0.95-1.07)	**1.13** (1.06-1.20)	**1.08** (1.03-1.13)
Q5	**1.10** (1.04-1.18)	1.02 (0.96-1.08)	1.02 (0.96-1.08)	1.02 (0.97-1.07)
p trend+	0.33	0.33	0.33	0.33
Continuous^	**1.02** (1.01-1.04)	**1.03** (1.01-1.04)	0.95 (0.85-1.06)	1.05 (0.96-1.15)

*death counts were stratified on age (19-64, 65+) and sex, as well as adjusted for percentages of population in each stratum in 15-year age categories

**death counts were stratified on age (19-64, 65+), sex, as well as adjusted for percentages of population in each stratum in 15-year age categories, percent of population in each census tract who is white, percent African American, percent with less than a high school education, percent with a Bachelor's degree or higher, and percent in poverty, median income, percent who commute greater than 30 minutes, percent who commute greater than 60 minutes, percent of the work force age population currently in the labor force, urbanity (1 if in Fulton/DeKalb, 0 if elsewhere) and interaction by age (19-64, 65+)

+Significance of Kendall's Tau

^Per 10 percentage point (absolute) increase in all greenspace and per 10 percent (relative) increase in public greenspace

Table 6. Multiple Imputations, equal interval exposure and quartile exposure, minimally stratified dataset

Coverage, total greenspace	No. of census tracts	Censored tracts	Adj. IRR (95%CI)*
>=20%	2	1	1.00
20%-40%	23	5	1.04 (0.78-1.38)
40%-60%	107	6	1.12 (0.90-1.40)
60%-80%	470	7	1.14 (0.92-1.41)
<80%	340	3	1.15 (0.92-1.42)
p trend+			**0.014**

*death counts were stratified on age (19-64, 65+), sex, as well as adjusted for percentages of population in each strata in 15-year age categories, percent of population in each census tract who is white, percent African American, percent with less than a high school education, percent with a Bachelor's degree or higher, and percent in poverty, median income, percent who

commute greater than 30 minutes, percent who commute greater than 60 minutes, percent of the work force age population currently in the labor force and urbanity (1 if in Fulton/DeKalb, 0 if elsewhere)
+Significance of Kendall's Tau

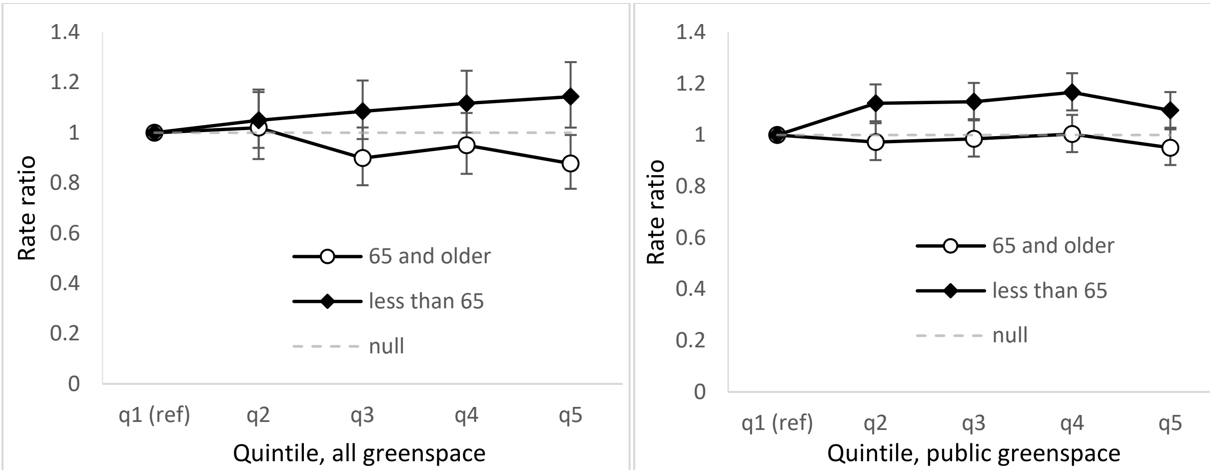

Figure 6. Rate ratios of mortality by quartile for people over the age of 65 vs 65 and over.