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Environmental Equity and Spatiotemporal Patterns of Urban Tree Canopy in Atlanta

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Abstract

While previous studies in environmental equity found positive relationships between tree canopy and socioeconomic/demographic status of neighborhoods, few examined how *changes* in tree canopy are associated with *changes* in socioeconomic/demographic status. This study confirms that the relationship between them in Atlanta is changing and the hypothesis of inequitable distribution of tree canopy concerning demographic attributes cannot be fully supported beyond 2000. In addition, the proportion of African Americans can have different effects on the estimated tree canopy as poverty rates vary. Planning to mitigate environmental inequities through tree plantings requires more careful analysis that goes beyond the socioeconomic/demographic attributes of the population.

Keywords

environmental equity, longitudinal analysis, urban tree canopy, vulnerability

Introduction

The geography of land use in a city is shaped by the distribution of resources and amenities available to residents, as well as their preferences and ability to access them (Landry and Chakraborty 2009). Residents with higher socioeconomic status tend to have more economic and political resources to select neighborhoods that meet their preferences and to prevent undesirable land uses and facilities from locating in those neighborhoods. While a healthy environment is a basic human right (United Nations 1993), past studies in the field of environmental equity have established that a variety of noxious land uses are disproportionately located in neighborhoods with low-income and minority populations (Bullard, Johnson, and Torres 2000; Sheppard et al. 1999; United Church of Christ Commission for Racial Justice 1987).

The literature on environmental equity incorporates not only the uneven distribution of undesirable land uses but also the skewed distribution of desirable amenities such as urban tree canopy (Landry and Chakraborty 2009). Trees are an important environmental amenity providing many benefits to urban residents. These benefits include stormwater management, air quality improvement with associated reductions in respiratory-related morbidity and mortality, increased building energy conservation through shading and cooling, and microclimate regulation, which in turn reduces heat-related morbidity and mortality (e.g., Nowak and Dwyer 2007; Nowak and Greenfield 2012a; Stone 2012). Some studies have found that an abundance of trees may encourage physical activity, which is associated with improved health outcomes (Donovan et al. 2013; Takano, Nakamura, and Watanabe 2002). Such benefits, however, are often disproportionately enjoyed by members of higher socioeconomic classes (Landry and Chakraborty 2009; Pham et al. 2012). Desirable features such as a dense urban tree canopy often increase housing prices and/or rents and would attract residents who can afford the higher housing costs associated with such features (Donovan and Butry 2011; Sander, Polasky, and Haight 2010) to the exclusion of those who cannot, resulting in inequitable access to this important amenity.

The provision of urban trees does not solely depend on public provision as urban trees are often located in residential lots. Yet, as noted by Mincey, Schmitt-Harsh, and Thurau (2013, 191), ". . . their canopies maintain ecosystem services that constitute public goods." Many municipalities maintain existing urban trees and plant new ones by setting tree canopy goals. They also encourage private actions to meet these goals by instituting appropriate policies (Mincey, Schmitt-Harsh, and Thurau 2013). With growing concerns about the impact of climate change, urban trees are increasingly regarded as critical infrastructure and frequently included in municipal initiatives for sustainability and climate change adaptation or mitigation (Bassett and Shandas 2010). For example, the Atlanta Climate Action Plan acknowledges that

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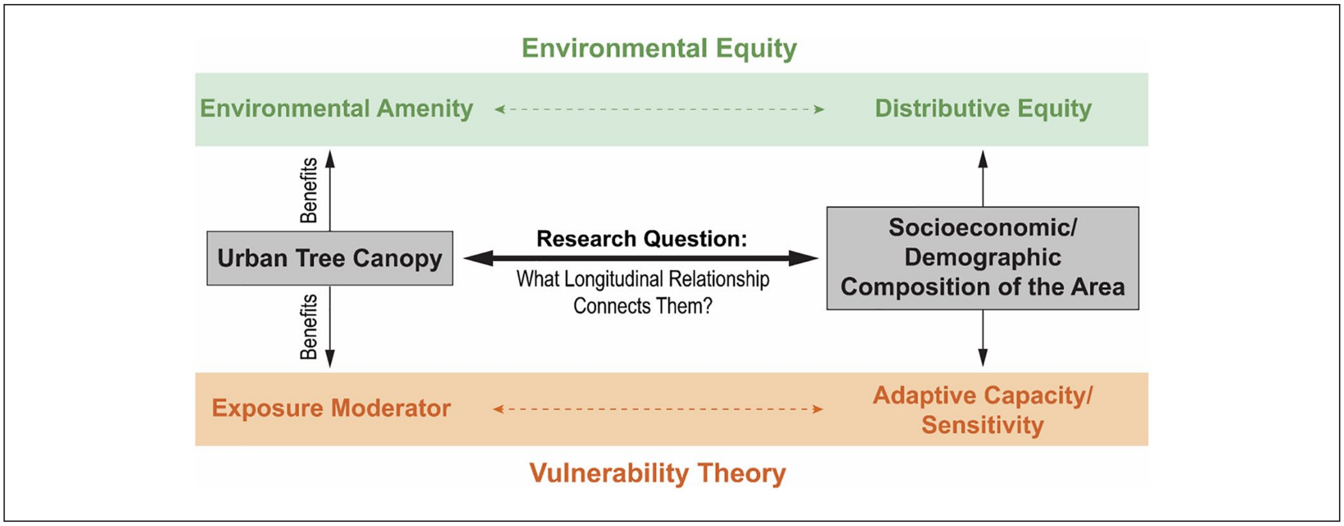

Figure 1. Theoretical framework of the study.

urban trees provide critical benefits such as carbon sequestration, temperature reduction, and energy conservation, and notes that increasing tree canopy is one of the city's primary foci (City of Atlanta 2015, 40).

Land use policies and accompanying zoning regulations are known to have an impact on the canopy cover (Hill, Dorfman, and Kramer 2010). Moreover, simply having tree-specific policies, such as a tree ordinance or a tree board, are shown to be ineffective without a more comprehensive set of planning regulations. For example, Hill, Dorfman, and Kramer (2010, 413) noted that "a set of tree ordinance clauses, zoning ordinances, and having high quality smart growth projects in the community" in combination is most effective in maintaining and expanding tree cover. These findings, along with the climate action plans incorporated in planning documents, indicate that planners play a critical role in maintaining and increasing the urban tree canopy.

What is less clear, however, is how increases or decreases in urban tree canopy over time are related to the improvement or decline of environmental equity. When an undesirable land use or facility is introduced into a neighborhood, residents of higher socioeconomic status tend to move out and residents of lower socioeconomic status replace them (Banzhaf and Walsh 2008). Conversely, when a favorable amenity is introduced into a neighborhood, it is likely that the benefits provided by the amenity will be disproportionately enjoyed by those who can either outbid others to stay or move into the neighborhood (Anguelovski 2016). This neighborhood sorting and the resultant inequitable redistribution of amenities and disamenities by socioeconomic class can reinforce and perpetuate spatial inequity. The majority of previous studies on the distribution of urban tree canopy cover have used cross-sectional models. Therefore, an understanding of how changes in tree canopy are linked with residential sorting has been limited. This is an important issue in the City of Atlanta as middle and high socioeconomic classes have gentrified many inner-city neighborhoods, which has altered the city's demographic and socioeconomic landscape (Aka 2010).

This study analyzes the changing patterns of the distribution of urban tree canopy cover at multiple points in time in the city of Atlanta and examines how this pattern is associated with the changes in the socioeconomic/demographic landscape. Particularly, it attempts to test the following hypotheses we derived from the environmental equity literature: (1) the neighborhoods with a high share of racial/ethnic minorities and/or socioeconomically disadvantaged residents will have lower coverage of urban tree canopy and (2) the neighborhoods in which the share of racial/ethnic minority increase and/or socioeconomic status of residents decline, will be associated with a decrease in urban tree canopy.

In the next section, we discuss the literature on which our study is based. The "Study Area, Data, and Methods" section introduces the methods and data, while the "Results" section presents the results of our analysis. Finally, this study concludes by summarizing important findings and suggesting potential policy implications.

Research Background

This study examines the relationship between urban tree canopy cover and neighborhood socioeconomic indicators from the perspective of environmental equity. In addition to environmental equity, vulnerability theory is incorporated into the theoretical framework given the growing relevance of the benefits of urban tree canopy in mitigating the impacts of climate change. As shown in Figure 1, the relationship between urban tree canopy cover and socioeconomic/demographic indicators is closely linked with the environmental equity framework and vulnerability theory.

Urban Tree Canopy and Environmental Equity

Socioeconomic status is known to be positively associated with urban tree canopy distribution, suggesting that residents of higher socioeconomic status are likely to have more urban tree canopy cover (Krafft and Fryd 2016; Landry and Chakraborty 2009; Schwarz et al. 2015). In Milwaukee, Heynen, Perkins, and Roy (2006) found that median household income and the proportion of non-Hispanic whites are positively associated with greater canopy cover, while the percentage of renters, vacancy, and Hispanic residents are negatively associated with canopy cover. Landry and Chakraborty (2009) examined how urban trees on residential parcels and street trees are related to socioeconomic indicators in Tampa, Florida. Using a series of cross-sectional spatial regression models, they found that residents with lower socioeconomic status are expected to have a lower share of urban trees. Indicators of socioeconomic status that were statistically significant include median household income, the share of renters, the proportion of African American residents ($p < .05$), and the proportion of Hispanic residents ($p < .1$). A study by Krafft and Fryd (2016) is one of a few longitudinal studies on urban tree canopy and environmental equity. For five Local Government Areas within inner Melbourne, Australia, the authors examined how indicators of socioeconomic status, including median household income, home ownership, and educational attainment, were related to tree canopy cover in both 2001 and 2011. Using rank order correlation and descriptive statistics comparing socioeconomic status in 2001 and canopy cover in 2011, they found that income in 2001 was the strongest predictor of tree cover in 2011, followed by the proportion of university graduates and homeowners.

Several studies have used hedonic models to estimate the contribution of tree canopy to property values, generally finding positive associations between them (Anderson and Cordell 1988; Morales 1980; Tyrväinen and Miettinen 2000). A study by Sander, Polasky, and Haight (2010) found that higher residential tree canopy cover contributes to higher property value, with the magnitude of the increase in property values varying according to distance from trees. Using two counties in Minnesota as study sites, they measured the contribution of tree canopy to property price by incrementally increasing buffer distance from 100 to 1,000 m from parcels. The result indicated that tree canopy cover within a 100- and 250-m buffer contributed to higher sale prices, and beyond that point tree cover is not significantly associated with housing price. Although some of these studies were conducted to verify that the benefits of urban tree canopy increase the desirability of residential properties and therefore increase demand for such properties, an important implication of these findings is that urban tree canopy cover may have a negative effect on housing affordability.

Urban Tree Canopy and Vulnerability Theory

The vulnerability of humans to environmental hazards is defined as "the degree to which they are likely to experience harm due to exposure" (Chow, Chuang, and Gober 2012, 288). Several scholars have noted that vulnerability is a function of exposure, sensitivity, and adaptive capacity (Gallopín 2006; Karner, Hondula, and Vanos 2015; Polsky, Neff, and Yarnal 2007; Turner et al. 2003). Sensitivity can be characterized by "underlying demographic factors that place particular populations at risk" (Karner, Hondula, and Vanos 2015, 453) when they are exposed to a hazard, including age and preexisting medical conditions. Adaptive capacity refers to "the ability to mitigate the risk" of harm from exposure through adaptive means such as air conditioning, access to cooling centers, landscaping, and other similar mechanisms (Chow, Chuang, and Gober 2012, 288). Sensitivity and adaptive capacity have been theorized to have close relationships with various socioeconomic/demographic characteristics (Chow, Chuang, and Gober 2012; Ngo 2001; Wolf and McGregor 2013). Cutter and Finch (2008, 2301) have noted that "race/ethnicity, socioeconomic class, and gender are among the most common characteristics that define vulnerable populations, along with age (elderly and children), migration, and housing tenure." In short, age, gender, race, and socioeconomic status are widely viewed as common characteristics for constructing vulnerability indices related to environmental hazards (Cutter, Boruff, and Shirley 2003). Regarding the relationship among sensitivity, adaptive capacity, and exposure, Smit and Wandel (2006, 286) observed,

> generally, a system (e.g., a community) that is more exposed and sensitive to a climate stimulus, condition or hazard will be more vulnerable, *ceteris paribus*, and a system that has more adaptive capacity will tend to be less vulnerable, *ceteris paribus*.

Because trees can be effective in mitigating various impacts of climate change (i.e., reducing exposure) by, for example, microclimate regulation, stormwater management, and air quality improvement, having sufficient tree canopy can be particularly important for those who have high sensitivity to extreme temperatures or pollution and/or low adaptive capacity for dealing with such impacts.

The variables used to construct sensitivity and adaptive capacity largely overlap with the variables commonly utilized in the environmental equity literature. To assess environmental equity, past studies often used indicators such as household income, race/ethnicity, housing tenure, educational attainment, and age. This overlap provides a pathway to link the uneven distribution of environmental amenities (or disamenities) and vulnerability. For example, the difference in vulnerability across socioeconomic groups would be greater when higher levels of exposure (e.g., less urban tree

Table 1. The Change in the City of Atlanta Population by Race between 2000 and 2013.

Year	African American	White	Asian	Other races	Total	Hispanic or Latino
2000	255,689 (61.4%)	138,352 (33.2%)	8,046 (1.9%)	14,387 (3.5%)	416,474	18,720 (4.5%)
2013	231,628 (53.5%)	170,176 (39.3%)	15,674 (3.6%)	15,111 (3.5%)	432,589	23,089 (5.3%)
Difference 2000–2013	−24,061	+31,824	+7,628	+724	+16,115	+4,369
Relative change	−9.4%	+23.0%	+94.8%	+5.0%	+3.9%	+23.3%

Note: The figures in the total column do not include Hispanic or Latino. Percentages in the parenthesis are the proportion of the racial/ethnic group.

cover) are coupled with higher levels of sensitivity or lower levels of adaptive capacity (e.g., lack of economic resources to cope with exposure, high sensitivity due to age or a preexisting medical condition, or the linguistic isolation of recent immigrants). Thus, given that urban trees can be an effective adaptation strategy that reduces the adverse impacts of climate change, the inequitable distribution of urban tree cover may translate to a higher risk of exposure for populations with higher sensitivity or lower adaptive capacity, widening the vulnerability gap.

Study Area, Data, and Methods

Study Area

The City of Atlanta, Georgia has two unique characteristics that make the city suitable for this study: (1) its abundant urban tree canopy, which was steadily declining, and (2) changes in racial composition in the neighborhoods. Atlanta, a city known as a "Black Mecca" (Brookings Institution 2000; Strait and Gong 2015), has seen a constant decline in the proportion of African American population while the proportion of white, Asian, and Hispanic residents has been steadily increasing. Table 1 shows the change in racial composition between 2000 and 2013. This change in racial composition has been "so dramatic that the city has outpaced all other U.S. cities in that category" (Jennings 2016, 3). Spatially, we find that the white population has grown in the inner-city area (Aka 2010; Strait and Gong 2015) and the nonwhite population has been increasingly suburbanized (Strait and Gong 2015). Accompanying this trend is gentrification, measured by changes in racial composition, income, and housing cost, which is occurring particularly in the inner-city area of Atlanta (Aka 2010).

Although Atlanta has been known for its thick tree canopy and its stringent tree protection ordinance, it was losing its canopy at a rate faster than many other major cities in the United States between 2005 and 2009 (Nowak and Greenfield 2012b). However, this rapid loss appears to have slowed down in more recent years: a recently updated report for 2014 indicates 47.1 percent of the land area within the city limits was covered in tree canopy (Giarrusso 2018), down slightly from the 2008 value of about 47.9 percent (Giarrusso and Smith 2014). Although the city-level average indicates a negligible reduction over the six years, there seems to exist a geographic clustering of increases and decreases. Particularly, the northern section of the city, which has traditionally been comprised of many affluent neighborhoods, experienced the most notable reduction in tree canopy between 2008 and 2014 (Giarrusso 2018). This tree canopy loss is occurring in spite of Atlanta's stringent tree protection ordinance (Stone 2012). There are efforts to increase tree canopy outside of the regulatory frame. Trees Atlanta, an organization working to prevent the loss of urban forest in the city, has planted more than 113,000 trees across Atlanta since its foundation in 1985 (Trees Atlanta n.d.) and provides other conservation education services.

Data Preparation

The study is conducted at the block group level within the city boundary using two cross-sectional models for 2000 and 2013 and a longitudinal model assessing the change between 2000 and 2009. Census block groups were chosen over tracts because the effect of tree canopy on property value, the major mechanism through which sorting may occur, is likely to be highly localized (Sander, Polasky, and Haight 2010) and may be more accurately captured at the block group scale. The data sources and the timeframe of the study were selected to ensure that the entire time span (i.e., 2000–2013) is long enough to accommodate the economic downturn in 2008 and subsequent recovery period. Also, the selection of the specific years was guided by the availability of reliable data for both tree canopy and the socioeconomic status of residents.

All socioeconomic and housing-related data were acquired from the U.S. Census Bureau at the block group level. Because the five-year estimate of the American Community Survey (ACS) became available since 2009, the initial year of this study was limited to use the 2000 Decennial Census. For cross-sectional models, data from the 2000 Decennial Census and the 2013 ACS were selected. For the longitudinal models, to avoid any bias that may be introduced by the change in census boundaries that occurred in 2010, we chose to match the 2000 Decennial Census and 2009 ACS data.

An ideal tree canopy data for this study would have a temporal range that is long enough to accommodate bust-and-recovery of the recent economic downturn while maintaining the consistency in collecting and processing methods over

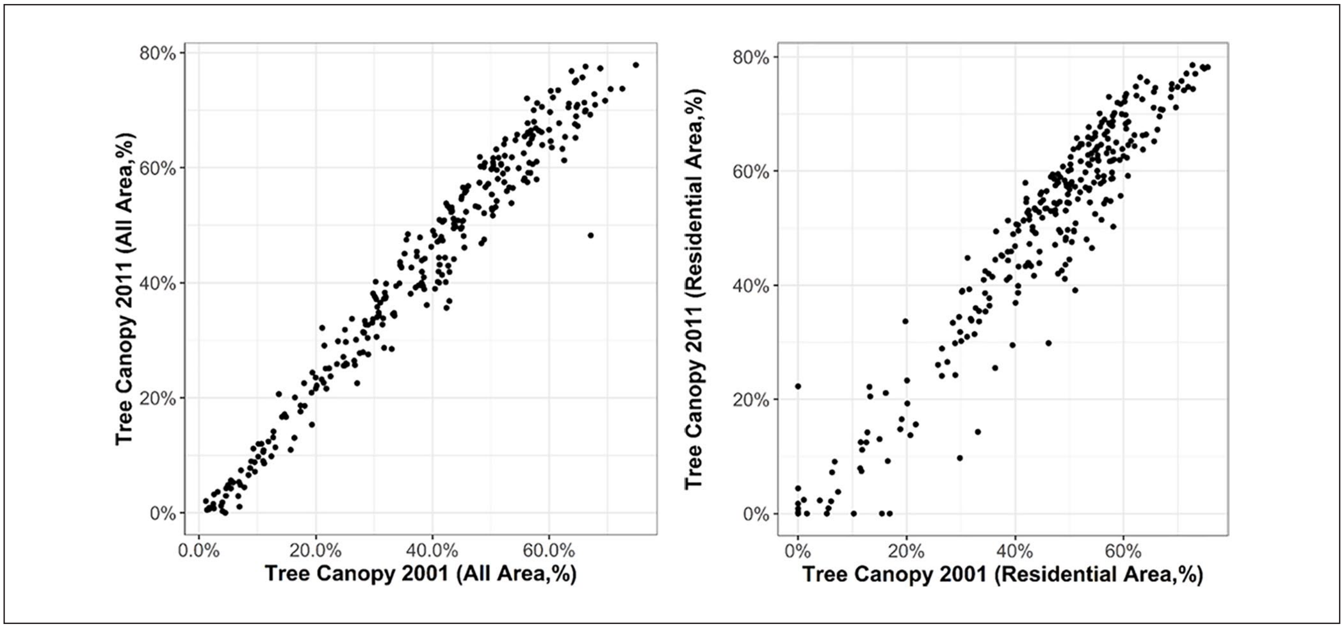

Figure 2. Scatterplot between NLCD 2001 and 2011 in the entire city area (left) and in the residential area (right).
Note: NLCD = National Land Cover Database.

the temporal range. Unfortunately, there was no single source of tree canopy data available that met the data criteria, and we acquired the tree canopy data from two different remote sensing data sets: (1) the National Land Cover Database (NLCD) and (2) the National Agricultural Imagery Program (NAIP). The NLCD is a preprocessed remote sensing data set with 30-m resolution and is available for 2001, 2006, and 2011 (Homer et al. 2007; Xian et al. 2011). We derived urban tree canopy estimates of 2001 for the first cross-sectional model and tree canopy estimates of 2001 and 2011 for the longitudinal model from NLCD because of its longitudinal span, comparability, and relatively well-aligned years with the census data. Note that the definition of trees used to generate tree canopy estimates in NLCD 2001 is different from that of NLCD 2011. In NLCD 2001, only trees taller than 5 m were considered for canopy estimates whereas NLCD 2011 did not have any height restrictions. Due to this restrictive definition, NLCD 2001 most likely underestimated the tree canopy (Nowak and Greenfield 2010), which may limit the comparability of these data sets. For the purpose of measuring distributional equity, the NLCD 2001 and 2011 can be compared without significant bias when the extent of the underestimation in NLCD 2001 is consistent across all study areas. If this assumption is valid, the coefficients and statistical significances of explanatory variables in regression models would not be considerably biased. As shown in Figure 2, NLCD 2001 and 2011 appear to be linearly concentrated around a straight line, and we concluded that NLCD 2001 and 2011 are reasonably comparable and can be used to study distributional equity. Because NLCD beyond 2011 was unavailable at the time of this writing, tree canopy data for 2013 was derived from NAIP Imagery. The NAIP imagery starts its coverage for the state of Georgia starting from 2005, and four-band, 1-m resolution aerial imagery became available after 2009. The imagery was classified using unsupervised iso-cluster classification in ArcGIS 10.1. After the initial image classification, misclassifications were manually adjusted by drawing masks. The overall accuracy for the classification was 85.6 percent.

The proportion of block group area covered by tree canopy is calculated only for residential areas for two reasons. First, the census data are based on the location of residences. Second, some block groups have large forested areas that do not overlap with residential areas. Therefore, using the entire block group area may not correctly reflect the residents' experience of the urban tree canopy in their daily lives or when they make a decision to move in or out of the block group. All tree canopy measures heretofore refer to the *residential* tree canopy unless stated otherwise. Residential areas for each year were identified using land use/land cover data provided by the Atlanta Regional Commission.

Explanatory variables were selected from two different fields of study, namely environmental equity and vulnerability theory. As mentioned above, there is an overlap in the attributes frequently used in both fields, and these were given priority in variable selection (Cutter, Boruff, and Shirley 2003; Grove et al. 2006; Heynen and Lindsey 2003; Jesdale, Morello-Frosch, and Cushing 2013; Krafft and Fryd 2016; Landry and Chakraborty 2009; Lowry, Baker, and Ramsey 2012; Pham et al. 2012; Troy et al. 2007). All variables were examined for normality before the analysis, and log transformation was applied when necessary. Some variables initially

Table 2. Descriptive Statistics of Variables Used in Regressions.

	Cross-section 1 ↓ ← Longitudinal model		→		Cross-section 2 ↓		
	2000		2009 (2011)		2013		
Variable	Minimum Maximum	*M* SD	Minimum Maximum	*M* SD	Minimum Maximum	*M* SD	Data source
Residential tree cover	0.000 0.755	0.453 0.169	0.000 0.786	0.498 0.198	0.000 0.851	0.493 0.187	NLCD (2001, 2011) NAIP (2013)
Population density (acre)	0.245 44.88	5.199 4.328	0.196 35.79	6.017 4.925	0.233 64.16	5.415 5.261	Decennial 2000 ACS 2009, 2013
% black (non-Hispanic)	0.000 0.988	0.635 0.391	0.000 1.000	0.587 0.395	0.000 1.000	0.542 0.390	
% Asian (non-Hispanic)	0.000 0.403	0.014 0.036	0.000 0.217	0.019 0.037	0.000 0.334	0.028 0.051	
% Hispanic	0.000 0.794	0.038 0.075	0.000 0.841	0.043 0.092	0.000 0.626	0.044 0.072	
% high school degree or less	0.020 1.000	0.500 0.281	0.000 1.000	0.4200 0.267	0.000 0.783	0.3200 0.229	
% renter-occupied housing	0.019 1.000	0.540 0.257	0.000 1.000	0.495 0.270	0.000 1.000	0.5180 0.266	
% under poverty	0.000 0.772	0.244 0.182	0.000 1.000	0.246 0.207	0.000 0.861	0.252 0.193	
Median building age (year)	3.00 61.00	41.00 11.53	—	—	9.00 74.00	43.96 18.90	

Note: NLCD = National Land Cover Database; NAIP = National Agricultural Imagery Program; ACS = American Community Survey.

tested in the analysis were excluded due to the high risk of multicollinearity. One caveat of using ACS at block group level is that it may have relatively large margins of error compared with, for example, tract-level estimates. For example, the average of 2009 Census estimate of the population with less than high school education is about 62 percent of the average margins of error. Similarly, the average estimate of Hispanic population in 2013 ACS is only slightly larger than the average of margins of error. Nonetheless, the 2000 Decennial Census collected approximately one sample out of every six households and therefore our analysis using the Decennial Census is based on much more accurate data. Moreover, many of the variables from the ACS that later constitute the core findings of this study, such as the number of African Americans, those under poverty, and renters, have average estimates that are at least two to three times larger than the average margin of errors, making the findings relatively more robust.

This study tested for an interaction effect between race and poverty. The proportion of white residents (or nonwhites/minorities) and the poverty rate have been frequently used to explain neighborhood location (Sampson and Sharkey 2008). Past studies have suggested a stratification by income within the same racial group, particularly for African Americans (Charles 2003; Gates 2016). We tested for interaction terms in all models for all possible combinations of racial categories and poverty rates and retained those that showed a significant effect for further interpretation. Table 2 shows descriptive statistics of the variables used in the regression models.

Data Analysis

Previous studies on similar topics have reported the issue of spatial autocorrelation. Spatial autocorrelation refers to a relationship between the spatial proximity of observational units and the similarity in their values (Lee 2017). For example, when observations that are geographically close to one another have similar (or dissimilar) values more frequently than spatially randomly distributed values, it is said to have a positive (or negative) spatial autocorrelation. The presence of spatial autocorrelation is a violation of the assumption of independent observations frequently used in standard statistical models. In this study, regression residuals from the ordinary least squares (OLS) models were tested for autocorrelation using the Moran's I statistic, which confirmed the presence of spatial autocorrelation in the OLS residuals.

One technique for correcting spatial autocorrelation is to use the simultaneous autoregressive (SAR) model, which includes spatial dependence effects in the standard linear regression model (Anselin and Bera 1998). The SAR model interprets the spatial relationship among observations (census block groups) using a spatial weight matrix, which contains information on whether observation A is adjacent to observation B. We used the rook contiguity measure to construct the weight matrix, in which census block groups that have common sides of the polygon boundaries are marked as 1, while block groups with no common sides are marked 0. There are various ways of addressing autoregressive effects in SAR models. The two most common approaches are spatial lag regression and spatial error regression. Spatial lag regression model (SAR_{lag}) assumes that the spatial dependency exists among the dependent variable, while spatial error regression model (SAR_{error}) assumes the spatial dependency occurs among the error term. The selection between SAR_{lag} and SAR_{error} can be done based on the Lagrange Multiplier test (Anselin 1988), which informed our model selection. The regression models used for the two cross-sectional models in our analysis are as follows:

$$\text{TREE} = c + \text{BUILT} + \text{SOCIO} + \rho \mathbf{W} y + \varepsilon,$$

where TREE is tree canopy cover in percentage; BUILT is the built environment characteristics (population density and median building age); SOCIO is the socioeconomic and demographic characteristics (ethnicity, educational attainment, poverty status, and percent renting); ρ is the spatial autoregression coefficient; $\mathbf{W}$ is the spatial weight matrix; y is the spatially lagged dependent variable; and ε is the error term.

Some modifications were made for the longitudinal model. First, tree canopy cover in 2011 was used as a response variable, and tree canopy cover in 2001 was entered as one of the explanatory variables. Despite the fact that tree canopy cover in 2011 was used as the dependent variable, the inclusion of tree canopy cover in 2001 as an explanatory variable means that the coefficients of other explanatory variables represent the relationship between the explanatory variable and the *change* in tree canopy cover between the two points in time. Second, the longitudinal model differs from the cross-sectional model in that it includes not only the explanatory variables measured in 2000 but also how much they changed over time (i.e., the difference between the values measured in the later year and the base year). The equation for the longitudinal model therefore is as follows:

$$\begin{aligned}\text{TREE}_{11} = c &+ \text{TREE}_{01} + \text{BUILT}_{00} + \Delta\text{BUILT}_{00\text{-}09} \\ &+ \text{SOCIO}_{00} + \Delta\text{SOCIO}_{00\text{-}09} + \lambda \mathbf{W} \upsilon + \varepsilon,\end{aligned}$$

where BUILT is the built environment characteristics (population density and median building age) and SOCIO is the socioeconomic and demographic characteristics (ethnicity, educational attainment, poverty status, and percent renting); suffix delta (Δ) denotes that it is the change between two years (e.g., $\Delta\text{SOCIO}_{00\text{–}09}$ represents the change in socioeconomic and demographic characteristics between 2000 and 2009); λ is the spatial autoregression coefficient; $\mathbf{W}$ is the spatial weight matrix; υ is the spatially dependent error term; and ε is the random error term. Note that for median building age, subtracting the median building age between two time points to assess how much older or younger a neighborhood's buildings are can have arbitrary meaning. Instead, we matched median building age measured in 2000 with the change in residential land area between the two time points.

Results

Figures 3 through 5 show residential urban tree canopy by census block group in 2001, 2011, and 2013. The estimates of residential tree canopy in those years are 45.3, 49.8, and 49.3 percent, respectively. Note that the estimate for 2001 may be lower than the latter years due to underestimation described earlier. Visual observation shows that the northern half of the city, which historically has been comprised of predominantly white neighborhoods, had the highest percentage of residential tree canopy in 2001. The southwestern part of the city, which has traditionally been comprised of African American neighborhoods, had a relatively less residential tree canopy in 2001. Figure 6 shows clusters of block groups that gained or lost residential tree canopy between 2001 and 2011.[1] The Downtown and Midtown areas (block groups in blue in Figure 6) are cold spots where clusters of block groups lost tree canopy, whereas the hotspots in which clusters of block groups showed increased tree canopy (block groups in red in Figure 6) are located in the southwestern part of the city.

Tree Canopy and Environmental Equity in 2000

Table 3 shows the regression result of the spatial lag model for the year 2000. Although not directly comparable to the R^2 statistics of the OLS models, pseudo R^2 statistics for the SAR model indicates an improvement in the model fit. Similarly, the Akaike information criteria (AIC) statistic indicates that the SAR model shows a better fit than the OLS model. The results of the OLS model are thus omitted in all the tables.

The result of the cross-sectional regression for the year 2000 shows estimates with directions that generally agree with past findings. Population density is significant and negatively associated with urban tree canopy. Median building age and its quadratic term are highly significant with the expected signs. The negative coefficient of the quadratic term suggests a downward concave curve, indicating that urban trees in residential areas increase at a faster rate in block groups with newer buildings than those with older buildings. After controlling for built environment factors, the

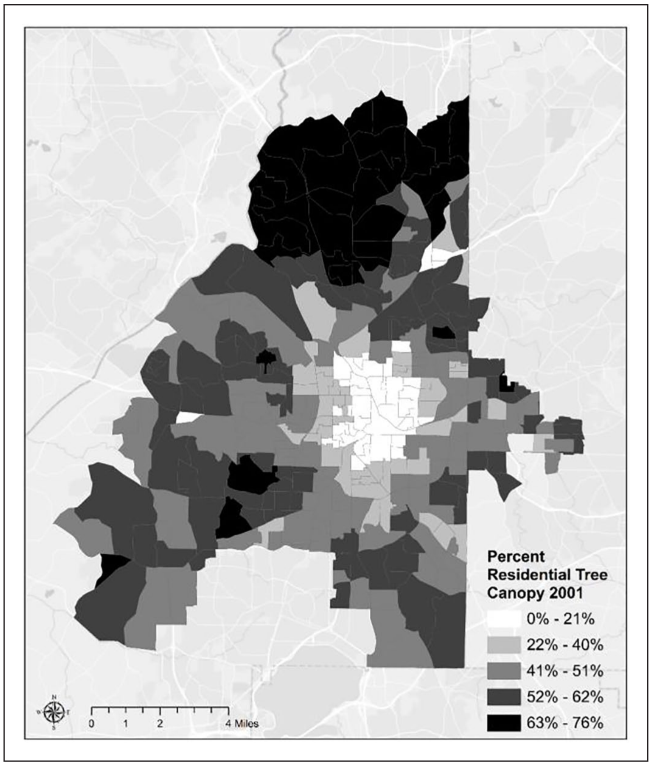

Figure 3. Percent residential tree canopy in 2001 in block group.

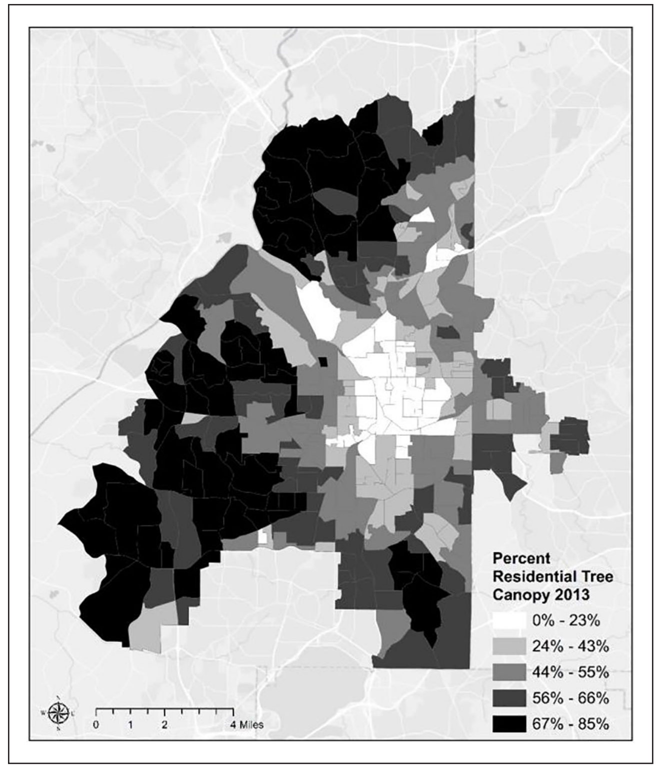

Figure 5. Percent residential tree canopy in 2013 in block group.

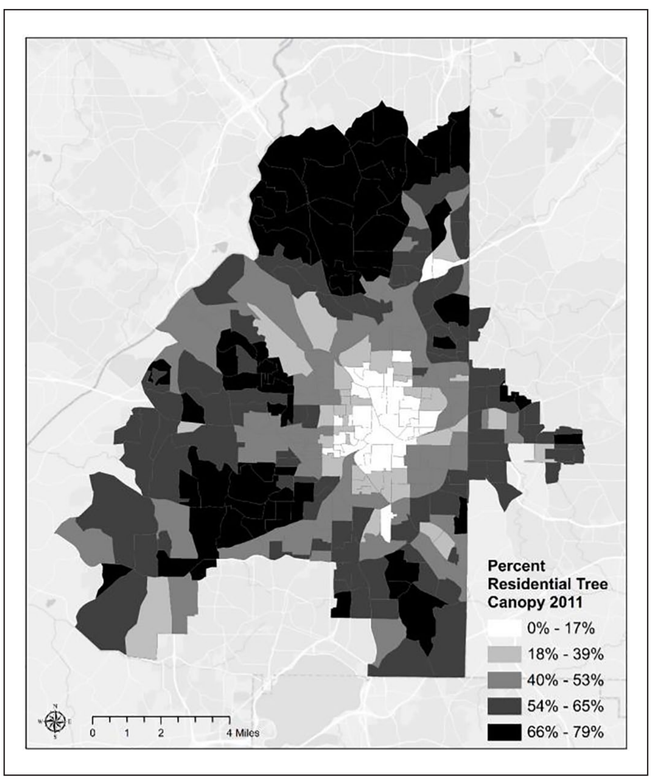

Figure 4. Percent residential tree canopy in 2011 in block group.

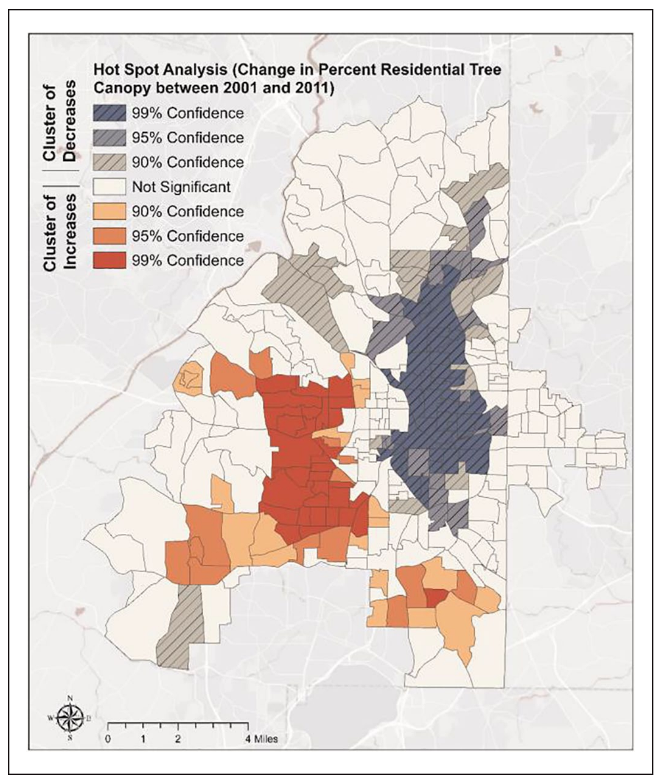

Figure 6. Change in percent residential tree canopy between 2001 and 2011.

Table 3. Cross-Sectional SAR_{lag} Model Result for Year 2000.

Dependent variable = TREE	Coefficient	*SE*	*z* value	*p* value
Rho	0.678	0.038	17.926	.000***
Constant	0.060	0.052	1.16	.247
Population density (ln)	−0.029	0.007	−4.42	.000***
Median building age	0.010	0.002	5.04	.000***
Median building age^2	−0.000	0.000	−4.50	.000***
% black	−0.051	0.029	−1.80	.071*
% Asian (ln)	−0.007	0.009	−0.78	.435
% Hispanic (ln)	−0.008	0.007	−1.10	.271
% high school degree or less	0.009	0.038	0.23	.815
% poverty rate	−0.074	0.040	−1.83	.068*
% renter-occupied housing	−0.140	0.025	−5.66	.000***
Number of observations	288			
Adjusted R^2 (OLS)	.617			
Nagelkerke pseudo R^2 (SAR)	.814			
AIC (OLS)	−470.47			
AIC (SAR)	−668.38			
Residual Moran's *I*	−0.001			Insignificant

Note: SAR = simultaneous autoregressive; OLS = ordinary least squares; AIC = Akaike information criterion.
*$p < .1$. **$p < .05$. ***$p < .01$.

proportions of African Americans ($p = .071$) and residents living in poverty ($p = .068$) are negatively associated with urban tree canopy cover at a marginally significant level, and the percentage of renter-occupied housing is negatively associated with urban tree cover ($p < .01$). These socioeconomic indicators generally point to lower adaptive capacity in vulnerability measures.

Explaining the Change in Tree Canopy between 2000 and 2009

Based on the Lagrange Multiplier test, we adopted the spatial error model for analyzing tree canopy change over 2000 and 2009 (Table 4). The results indicate that urban tree canopy in residential areas in 2000 is associated with the positive changes in tree canopy between 2001 and 2011. Among the built environment variables, an increase in the total land area of residential uses between 2000 and 2009 is associated with a decrease in percent tree cover during that period. An increase in residential areas can indicate new residential developments, and urban trees in such areas are likely to be newly planted, younger, and smaller. The positive estimate for population density measured in 2000 may seem counterintuitive but it actually makes sense; more densely populated areas in the past had less tree canopy to begin with and thus were more likely to increase than decrease. Contrary to the cross-sectional model for the year 2000, the result of the longitudinal model showed a changing trend in the relationship between urban tree cover and socioeconomic and demographic indicators. The percentage of African Americans in 2000 was positively and significantly associated with the change in urban tree cover. However, this relationship did not hold for the proportion of other racial or ethnic groups. The change in the percentage of residents with a high school degree or less was positively associated with the change in percent tree cover. This result, together with the estimates of African Americans in 2000, indicates some improvements in environmental equity. However, the proportion of renter-occupied housing remained negatively associated with the change in urban tree cover.

The interaction term composed of the change in the proportion of African Americans and the change in the poverty rate was significant at $p < .05$. It indicates that the effect of the changes in the proportion of African Americans can be different depending on the value of the change in the poverty rate and vice versa. Figure 7A shows the estimated tree canopy 2011 when the poverty rate is assumed to have increased by 17.8 percent over the years (90th percentile of the change in the poverty rate). Other variables are held constant at their mean. Under this assumption, an increasing change in the proportion of African American is associated with a lower 2011 tree canopy estimate. In contrast, if we assume that the poverty rate had dropped by −17.5 percent (10th percentile of the variable), an increasing change of the proportion of African American is positively associated with a higher 2011 tree canopy estimate. This relationship is shown in Figure 7B. Although differences in the estimated urban tree canopy shown in Figure 7 may appear to be marginal, it should be noted that the estimates shown in the figures are based on 10th and 90th percentile values; in the most extreme cases, the difference in the estimated tree canopy cover can be as large as over 20 percent.

Table 4. Longitudinal SAR_{error} Model Result.

Dependent variable = Tree 09	Without interaction		With interaction	
	Coefficient	Z	Coefficient	Z
Lambda	0.377***	5.10	0.391***	5.35
Constant	−0.003	−0.09	−0.005	−0.13
Tree 00	1.089***	34.94	1.085***	34.80
Median building age 00	−0.000	−0.64	−0.000	−0.65
Population density 00 (ln)	0.021***	3.97	0.020***	3.92
% black 00	0.074***	3.07	0.066***	2.71
% Asian 00 (ln)	0.004	0.56	0.003	0.48
% Hispanic 00 (ln)	−0.002	−0.37	−0.003	−0.58
% high school degree or less 00	0.009	0.27	0.015	0.46
% poverty rate 00	−0.033	−0.98	−0.032	−0.97
% renter-occupied housing 00	−0.072***	−3.75	−0.071***	−3.71
Residential area 00–09	−0.157***	−3.33	−0.157***	−3.37
Population density 00–09	−0.000	−0.33	−0.001	−0.81
% black 00–09	0.027	0.92	−0.002	−0.07
% Asian 00–09	−0.052	−0.63	−0.086	−1.03
% Hispanic 00–09	−0.020	−0.44	−0.040	−0.85
% high school degree or less 00–09	0.089***	4.07	0.099***	4.45
% poverty rate 00–09	0.002	0.10	−0.015	−0.61
% renter-occupied housing 00–09	−0.028	−1.18	−0.031	−1.32
% Black 00–09 × % Poverty Rate 00–09			−0.163**	−1.99
Number of observations	288		288	
Adjusted R^2 (OLS)	.937		.938	
Nagelkerke pseudo R^2 (SAR)	.944		.945	
AIC (OLS)	−893.95		−894.79	
AIC (SAR)	−909.26		−911.72	

Note: SAR = simultaneous autoregressive; OLS = ordinary least squares; AIC = Akaike information criterion.
*$p < .1$. **$p < .05$. ***$p < .01$.

Tree Canopy and Environmental Equity in 2013

The results from the cross-sectional spatial lag model for 2013 are presented in Table 5. The indicators representing built environment characteristics, namely population density and building age and its squared term, were all significant at $p < .01$ with the same direction of associations observed in the cross-sectional model for 2000. After controlling for the built environment and building age, the percentage of African Americans and Hispanics were positively associated with urban tree cover in 2013 at a marginally significant level ($p < .1$) and a significant level ($p < .05$), respectively. These results extend the findings from the longitudinal model and confirm that the proportions of African Americans and Hispanics are in fact predictors of greater urban tree cover in 2013. However, the poverty rate and the proportion of renter-occupied housing contribute negatively to urban tree cover, indicating that the deficit of economic resources continues to be a significant predictor of low tree canopy cover.

Discussion

The results of this study reveal that the conventional theories of inequity from which we derived our hypotheses do not conform to our data. Therefore, their applicability in framing policy responses needs to be tested for each context. Reflecting on the first hypothesis posed in the introduction, the cross-sectional model from 2000 shows that neighborhoods with a larger share of African Americans, residents in poverty, and renters were associated with a lower tree canopy cover than their counterparts, thereby supporting the hypothesis. In 2013, however, the racial minority was no longer a significant predictor of environmental inequity; rather, neighborhoods with a larger share of African Americans and Hispanics are associated with a greater tree canopy. The evidence that the conventional environmental inequity hypothesis conformed to the 2000 data but not to 2013 data upholds the argument that the relationship between minority concentration and tree canopy changed over time. Nonetheless, poverty and renter-occupied housing were consistently associated with greater environmental inequity in 2013, indicating that some parts of the conventional theory are still valid in the case of Atlanta.

The second hypothesis, which suggested that neighborhood tree canopy cover would decrease with the increase in racial/ethnic minority and/or the decline in socioeconomic status of residents over time, is only partly supported by our

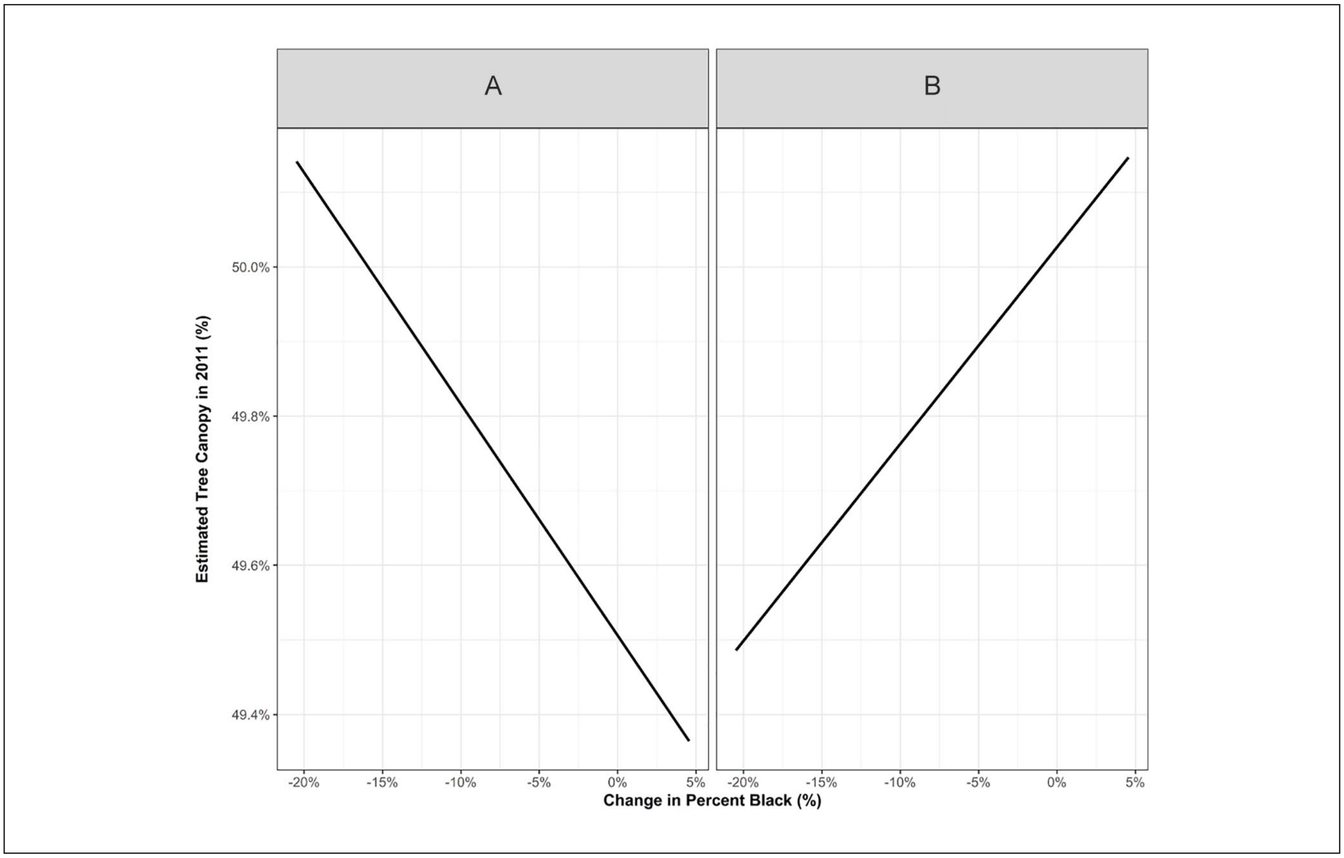

Figure 7. The effect of the change in percent African American on estimated urban tree canopy in 2011 depending on the change in percent under poverty: (A) estimated 2011 tree canopy when poverty rate is assumed to have significantly risen (17.8%) and (B) estimated 2011 tree canopy when poverty rate is assumed to have significantly dropped (−17.5%).

Table 5. Cross-Sectional SAR_{lag} Model Result for Year 2013.

Dependent variable = TREE	Coefficient	*SE*	*z* value	*p* value
Rho	0.651	0.038	17.279	.000***
Constant	0.171	0.040	4.25	.000***
Population density (ln)	−0.049	0.008	−6.36	.000***
Median building age	0.007	0.001	5.58	.000***
Median building age^2	−0.000	0.000	−4.65	.000***
% black	0.044	0.026	1.72	.085*
% Asian (ln)	0.000	0.006	−0.03	.980
% Hispanic (ln)	0.011	0.005	2.06	.040**
% high school degree or less	0.041	0.044	0.94	.346
% poverty rate	−0.115	0.039	−2.99	.003***
% renter-occupied housing	−0.114	0.025	−4.50	.000***
Number of observations	307			
Adjusted R^2 (OLS)	.624			
Nagelkerke pseudo R^2 (SAR)	.805			
AIC (OLS)	−446.81			
AIC (SAR)	−636.83			
Residual Moran's I	−0.039			Insignificant

Note: SAR = simultaneous autoregressive; OLS = ordinary least squares; AIC = Akaike information criterion.
**p* < .1. ***p* < .05. ****p* < .01.

data. In the longitudinal model, the block groups that had a higher proportion of African Americans in 2000 experienced an increase in tree canopy. Also, block groups in which the proportion of residents with a high school degree or less had risen experienced an increase in tree canopy over time. However, similar to the 2013 cross-sectional model, the proportion of renter-occupied housing in 2000 was associated with a decrease in tree canopy over time. The interaction term in the longitudinal model revealed that the change in the percentage of African Americans can have an opposite effect depending on the level of change in the poverty rate. In short, the ways in which socioeconomic status is associated with neighborhood tree canopy has been diverging from our hypothesis.

Although the findings of this study only partly support the hypotheses derived from conventional theories, they do conform to the racial redistributive trend in Atlanta. A large proportion of African Americans moved from the inner-city areas to the outskirts where tree canopy is relatively abundant, while residents of higher socioeconomic status, many of whom are white, have moved to inner-city areas where tree canopy coverage is low. This racial redistribution can be partly explained by the changing preference of residential locations and the degree to which the preference is realized. In Atlanta, a significant proportion of residents preferred walkable neighborhoods with good accessibility to shops and services but often ended up in less optimal choices due to undersupply of such communities (Frank, Levine, and Chapman 2004). Recent effects of gentrification may have supplied quality housing and neighborhoods in the inner-city area, bringing in affluent whites to areas that are more walkable and accessible but lack adequate tree canopy.

More detailed descriptive statistics of our data also lend support to this explanation. If we break down the tree canopy distribution in 2013 into five bins using quintiles, a large portion of the Atlanta Beltline, a large redevelopment project on an abandoned rail line that encircles the inner-city area of Atlanta, falls into the second quintile (i.e., the block groups with the second lowest tree canopy coverage). The Beltline has increased property values within 1.5 miles of the project (Immergluck and Balan 2018). The proportion of whites and those with a bachelor's degree or higher is the highest in this second quintile (50.7% and 52.6%, respectively), and the poverty rate is the lowest in this quintile (19.7%) in 2013. Note that in 2000, it was the fifth quintile (i.e., the block groups with the highest tree canopy coverage) that had the highest share of whites and those with bachelor's degree or higher and the lowest poverty rate. Still, the poverty rate is highest in the most tree-sparse quintile in both 2000 and 2013 (44.5% in 2000 and 33.8% in 2013). Similarly, when we tested adding the distance from the centroid of the block groups to the Atlanta Beltline into the 2000 cross-sectional model, which is before planning and public discussion of the Atlanta Beltline had started, this variable was insignificant and had minimal influence on other variables. However, in 2013 cross-sectional model, the distance to Beltline variable showed a statistically significant positive association with the tree canopy cover. Moreover, it rendered the share of African Americans insignificant ($p = .305$) and the share of Hispanics marginally significant ($p = .077$), suggesting that the development of the Atlanta Beltline may have been a citywide force affecting the relationship between African Americans and Hispanics and urban tree canopy in Atlanta.

This changing relationship between socioeconomic status of residents and urban trees has been rarely reported in past studies and offers novel insights for future planning and policy initiatives to improve environmental equity and to address the vulnerability of residents. First, the efforts to maintain canopy cover, especially in low-income and minority neighborhoods, will become increasingly important. African Americans and Hispanics are more likely than other racial groups to remove trees in their lots because they tend to lack resources to maintain trees (Heynen, Perkins, and Roy 2006). In Milwaukee, many large, under-maintained trees in minority neighborhoods are removed at a rate faster than intentional planting, which could lead to greater inequity (Heynen, Perkins, and Roy 2006). In addition, the interaction term in the longitudinal model suggests that areas where an increase in poverty rate is coupled with an increase in the share of African Americans can "lose" tree canopy over time. Although further research is needed to confirm whether the loss in tree canopy was actually due to the intentional tree removal caused by the maintenance cost, providing resources to maintain and preserve tree canopy to neighborhoods where poverty and racial minority status overlaps would be beneficial for improving environmental equity as well as mitigating vulnerability.

Second, the indicators used to identify the target areas where trees are most needed can be refined. The planning literature strongly argues for the importance of data-driven planning for tree-planting initiatives (Garrison 2018; Young 2011), and our analysis further suggests that using the right indicators to identify target areas can be critical in achieving environmental equity and reducing vulnerability. Although the racial minority status and poverty rate or low household income are typical factors discussed in the literature on disproportionate environmental impacts (Garrison 2018), minority status in Atlanta does not necessarily indicate higher vulnerability to environmental hazards unless it is coupled with other adverse socioeconomic conditions. The persistent inverse relationships between the tree canopy and both the poverty rate and the proportion of renters suggest that these factors can be effective in identifying areas for tree plantings, thereby fine-tuning the strategies for improving environmental equity and closing the vulnerability gap. High poverty areas are likely to have much greater vulnerability to environmental hazards than other areas given their lack of sufficient tree cover that moderates the risk of environmental hazard exposure and their limited resources to cope with the exposure. Furthermore, poverty and poor health conditions are known to coexist (Wagstaff 2002). A poor health condition may imply higher sensitivity, creating a hotspot of vulnerability. For these vulnerability hotspots, policy interventions for increasing tree canopy are imperative because poverty limits the ability of residents to invest in their properties and neighborhoods by planting trees, and renters tend to be less motivated to make such investments because they are usually not the beneficiaries of increased property value (Perkins, Heynen, and Wilson 2004).

In addition, this changing relationship indicates that findings from the literature may need to be tested and compared with the local context before utilizing them to develop local tree-planting plans. We stress the importance of the "local context" because of the heterogeneity of cities: factors such as climate, demographics, and city size that are unique to each city can lead to different relationships between urban tree canopy and socioeconomic/demographic characteristics of residents (Schwarz et al. 2015). In the review of the "Million Trees" planting campaigns in Los Angeles and New York City, Garrison (2018) reports that some major planting partners implied that prioritizing planting in low-canopy neighborhoods would improve environmental equity because such neighborhoods are typically where environmental justice measures, such as low-income and racial minority status, overlap. She further writes that both campaigns were "tacitly assuming that achieving this admittedly impressive goal would inevitably also contribute to greater environmental justice" (Garrison 2018, 6). Our analysis demonstrates that applying this assumption to Atlanta in 2013 may have resulted in unintended results. Furthermore, tree canopy assessment studies note the impact of land use planning and zoning regulation as having a profound effect on urban tree canopy distribution (Giarrusso and Smith 2014; Merry et al. 2014). For example, most of the tree canopy in Atlanta was found on single-family residential properties, followed by multi-family residential uses (Giarrusso and Smith 2014). The majority of the tree losses between 2008 and 2014 have happened on private property where trees were removed to maximize the building coverage up to allowable lot coverage (Giarrusso 2018). This calls for local planners to take a more active role in policy initiatives related to urban tree canopy, given their in-depth understanding of the relationship between land use planning and tree canopy distribution as well as about changing demographic landscapes that are unique to each city. This knowledge can be essential in determining, planning, and updating tree-planting and maintenance plans (Young 2011).

It is important to clarify limitations of this study. First, the temporal difference in the longitudinal model between NLCD 2011 and ACS 2009 might have introduced some bias in the results of the analysis. The degree to which the change in the definition of trees in NLCD 2001 and 2011 introduced biases is similarly unknown. Second, because ACS is based on survey data with limited sample size, the margins of error of the estimates can be greater for smaller geographic scales (e.g., block group level). Third, although results from the models using NLCD 2001 and 2011 appear to be in alignment with the results from the model using NAIP, the extent of biases that may have been introduced by the differences in the two remote sensing data sets is unknown. Fourth, this study treats tree canopy as a proxy of its benefits. The actual benefits as experienced by the beneficiaries may vary depending on various factors including specific tree species or the general health of the tree canopy. Furthermore, this study does not explicitly consider the possible negative impacts of tree canopy. As briefly mentioned in the discussion, some people can perceive tree canopy as an amenity while others can perceive it as a nuisance. Finally, this study does not identify or explicitly incorporate the causes of the changes in the distribution of tree canopy over time. Regardless of these limitations, the overall results are robust enough to suggest that the relationships among socioeconomic conditions and tree canopy cover is not time-invariant and can even be contextual depending on the changes in residents' preferences.

Policy Options for Equitable Distribution of Tree Canopy Benefits

A few planning/policy suggestions for providing equitable access to the benefits of urban trees and addressing the vulnerability of residents can be derived from this study. First, the afforestation priority in the Atlanta Tree Protection Ordinance can be modified to incorporate economic marginalization, particularly where a growing share of minorities accompanies an increase in poverty. Currently, the ordinance prioritizes the planting efforts in areas that need heat island mitigation or soil stabilization. Adding vulnerability of residents to the criteria can help fine-tune the target area and thus maximize the benefits from the investment.

Second, our data indicate that the inner-city area remains a hotspot where a high poverty rate, a high proportion of renters, and the lack of tree canopy coexist. The ordinance can be leveraged to allow replacement trees to be planted in places outside of the Neighborhood Planning Unit (NPU) from which they were removed and direct them to areas that continuously lack tree canopy. At the time of this writing, the ordinance requires that trees that are removed from an NPU need to be relocated in the same NPU or within 1 mile from the boundary of the NPU. This means an NPU with few trees to begin with will continue to have fewer trees if no additional planting initiatives exist. From a long-term perspective, incentive-based policy tools aimed at increasing potential planting spaces can be useful for areas that lack such spaces. For example, zoning concessions (i.e., floor area ratio bonus) can be offered to developers who agree to provide public spaces in their lots (e.g., see Kayden 2000). These public spaces can be valuable spaces for tree planting which otherwise may be expensive to acquire.

Third, from the vulnerability perspective, alternative approaches may also need to be considered, including high albedo roofs, green roofs, green factor programs (i.e., a score-based code requirement aiming at increasing the amount and quality of landscaping), or other similar tools that are less restricted by planting spaces but provide benefits similar to that of urban trees (Stone 2005). Green roofs, for instance, can provide ecosystem services such as stormwater management, regulation of building temperature, and reduction of the urban heat island effect (Oberndorfer et al. 2007). This approach can be important because even if we assume a sufficient planting of trees in areas where the lack of tree canopy coincide with high sensitivity and/or low adaptive capacity, the time it takes for trees to grow may hinder a timely provision of the needed benefits.

Urban trees provide various benefits to the residents, many of which can function as effective mitigators of the impact of climate change. The equitable distribution of urban trees is an important consideration for both promoting environmental justice and reducing the vulnerability of residents, particularly for those who have high sensitivity and/or low adaptive capacity. As planning and policy interventions for more equitable distribution of urban trees take time to implement, and because the relationship between socioeconomic conditions and tree canopy can change over time, any such intervention should incorporate a longitudinal perspective to ensure that desired outcomes are achieved. Future research should pay attention not only to the current cross-sectional relationship between tree canopy and socioeconomic status of residents but also to how the pattern changes over time.

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Note

1. As the National Land Cover Database (NLCD) 2001 is known to be underestimating the coverage of urban tree canopy, an increase in Figure 6 may be overestimated and a decrease may be underestimated.

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