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How Environmental Justice Patterns are Shaped by Place: Terrain and Tree Canopy in Cincinnati, Ohio, USA

Understanding the spatial distribution of environmental amenities requires consideration of social and biogeophysical factors, and how they interact to produce patterns of environmental justice or injustice. In this study, we explicitly account for terrain, a key local environmental factor, while assessing whether tree canopy is distributed equally in Cincinnati, Ohio, USA. We conducted separate analyses for all land and for residential land only. For all land, terrain alone accounted for 59% of the variation in tree canopy cover. In our spatial autoregressive model, socioeconomic variables describing race, wealth, and education did not explain significant variation in canopy cover. In other words, terrain is the primary factor related to tree canopy in Cincinnati. In our analysis of residential land only, terrain was again the dominant predictor of tree canopy cover, and percent black population and median home value were also positive, significant explanatory variables. Tree canopy was abundant in two hilly areas with dissimilar socioeconomic characteristics, with proportionally larger black populations in the western hills and higher home values in the eastern hills. In summary, the overwhelming importance of terrain may obscure subtler patterns between tree canopy and socioeconomic variables. Although general social processes may drive environmental injustice across disparate cities, our study highlights the need to account for local biogeophysical context.

Keywords

environmental justice, socio-ecological systems, urban forestry, urban tree canopy, stormwater management, green infrastructure

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INTRODUCTION

Historically, the field of environmental justice has focused on the unequal distribution of environmental hazards, often using individual case studies to demonstrate such patterns. More recently, this focus has expanded to include environmental amenities (Boone 2008; Boone et al. 2009). Methodological approaches have also broadened, using comparative studies to determine 1) if patterns of unequal distributions are consistent across space and time, and 2) if the drivers of those patterns are similar among cities that differ in age, social structure, and biogeophysical characteristics (Downey 2007; Mohai and Saha 2007; Schwarz et al. in review). The central aim of these approaches is the same – to identify the mechanisms that drive the unequal distribution of hazards or amenities in the environment.

Environmental justice theories can be evaluated by analyzing the distribution of the urban forest within urban areas. The urban forest, defined here as all woody vegetation in a city, can improve the quality of life for urban residents as an environmental amenity (Escobedo et al. 2011). For example, trees are an important component of green infrastructure that provide environmental benefits such as regulation of urban heat island effects (Hardin and Jensen 2007) and reduction of urban stormwater runoff (Xiao and McPherson 2002). The urban forest can have positive effects on human health and well-being (Tsunetsugu et al. 2013) and provide recreational opportunities (Bolund and Hunhammar 1999). Furthermore, property values are bolstered by the presence of street trees (Donovan and Butry 2010) and by proximity to forested areas (Tyrväinen and Miettinen 2000). Considering these positive impacts, the equal distribution of urban forest resources and associated benefits with respect to population characteristics such as race, wealth, and education is a goal of the environmental justice community. In this vein, researchers have noted situations in which the unequal distributions of urban vegetation may signal instances of environmental injustice (Pedlowski et al. 2002; Heynen and Lindsey 2003; Heynen et al. 2006; Landry and Chakraborty 2009).

Urban areas are prime examples of coupled human-environment systems (Grimm et al. 2000; Liu et al. 2007; Pickett et al. 2011), as they are influenced by both human factors (e.g., social preferences and norms, policies, economic constraints) and environmental context (e.g., climate, topography, hydrology). Consideration of both human and environmental factors is necessary to understand the underlying processes driving urban ecological patterns (Redman et al. 2004). However, urban ecological theories may be difficult to generalize across urban areas because both social and environmental aspects vary geographically, and these systems exhibit complex aspects when studied together (Liu et al. 2007). As a result, local social and/or environmental contexts may affect the expected ecological pattern resulting from a given process, such that theorized general patterns may be obscured by a locally important process.

The urban forest is an instructive example of an inherently human-environment resource. Urban forest structure—a characterization of tree abundances, sizes, species, health, and spatial arrangement—varies according to natural factors, urban morphology, and management decisions (Sanders 1984). Urban tree canopy has commonly been used to represent urban forest structure because it can be estimated relatively inexpensively using remotely sensed imagery (Moskal et al. 2011), and it is relevant because many communities, including New York City (McPhearson 2011) and Los Angeles (McPherson et al. 2011), set urban forestry goals based on canopy cover (i.e., the proportion of land surface covered by tree leaf canopies). Several researchers have accounted for the complicating factors at play in human-environment systems by including both types of data when studying the distribution of urban vegetation. For instance, Danford et al. (2014) considered limitations imposed by available physical space for tree planting when assessing future scenarios for urban tree canopy cover relative to socioeconomic conditions in Boston, Massachusetts. In another example, Lowry et al. (2012) analyzed several environmental variables related to water availability alongside indicators of socioeconomics and urban form in their assessment of urban tree canopy in the semi-arid region of Salt Lake County, Utah. However, in temperate areas, tree canopy cover may be more strongly related to terrain than other environmental factors like water availability. Indeed, in Sheffield, England, the slope of the land was a stronger predictor of tree cover than variables related to land use type and intensity (Davies et al. 2008). Similarly, Heynen and Lindsey (2003) noted a significant positive relationship between slope and urban tree cover in central Indiana.

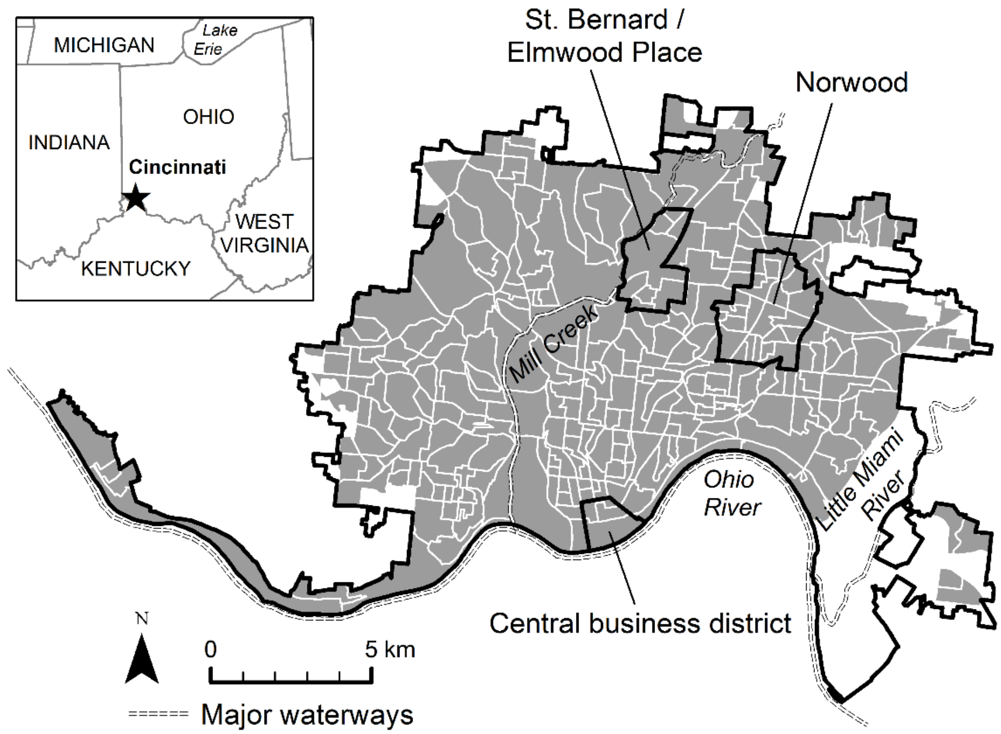
The inclusion of local environmental context may improve environmental justice research (Clark et al. 2007). In this study, we explicitly account for a key local biogeophysical factor while assessing whether an environmental amenity is distributed equally. Specifically, we investigate the potential role of terrain in modifying the expected patterns in urban tree canopy relative to race, wealth, and education. In doing so, our goal is not to conduct an exhaustive analysis of the relationships among urban forest patterns and underlying physical/socioeconomic drivers, but rather to assemble a relatively simple model to gain a better sense of how local environmental context may modify expected environmental justice patterns regarding the distribution of an environmental amenity. Although we focus exclusively on the spatial distribution of urban trees and not urban forest quality or community preferences, we address these nuances, specifically the contrast between equity and justice, in the discussion.

MATERIALS AND METHODS

Study Area

This study was conducted in Cincinnati, Ohio, USA, including the enclave cities of Norwood, Elmwood Place, and St. Bernard (Figure 1). Together, Cincinnati, Norwood, Elmwood Place, and St. Bernard (hereafter Cincinnati) had a 2011 population of 298,446 comprised primarily of white (53.4%) and black or African American (41.3%) residents (US Census Bureau 2011a). Cincinnati is located in the USA's Central Lowland physiographic province, and the area is characterized by gently rolling uplands and steep slopes buffering major streams (Lerch et al. 1982). The Ohio River borders the city to the south. Based on a 3-m resolution digital elevation model (Gesch et al. 2002), Cincinnati's elevation ranges from 138-293 m (456-961 ft) above sea level, with a mean of 201 m (659 ft).

Figure 1. The Cincinnati study area in southwest Ohio. Shaded polygons with white boundaries represent Census block groups with ≥95% of their area within Cincinnati's boundary (*n*=285). The study area includes the enclave municipalities of Norwood, Elmwood Place and St. Bernard. The central business district is shown for reference.

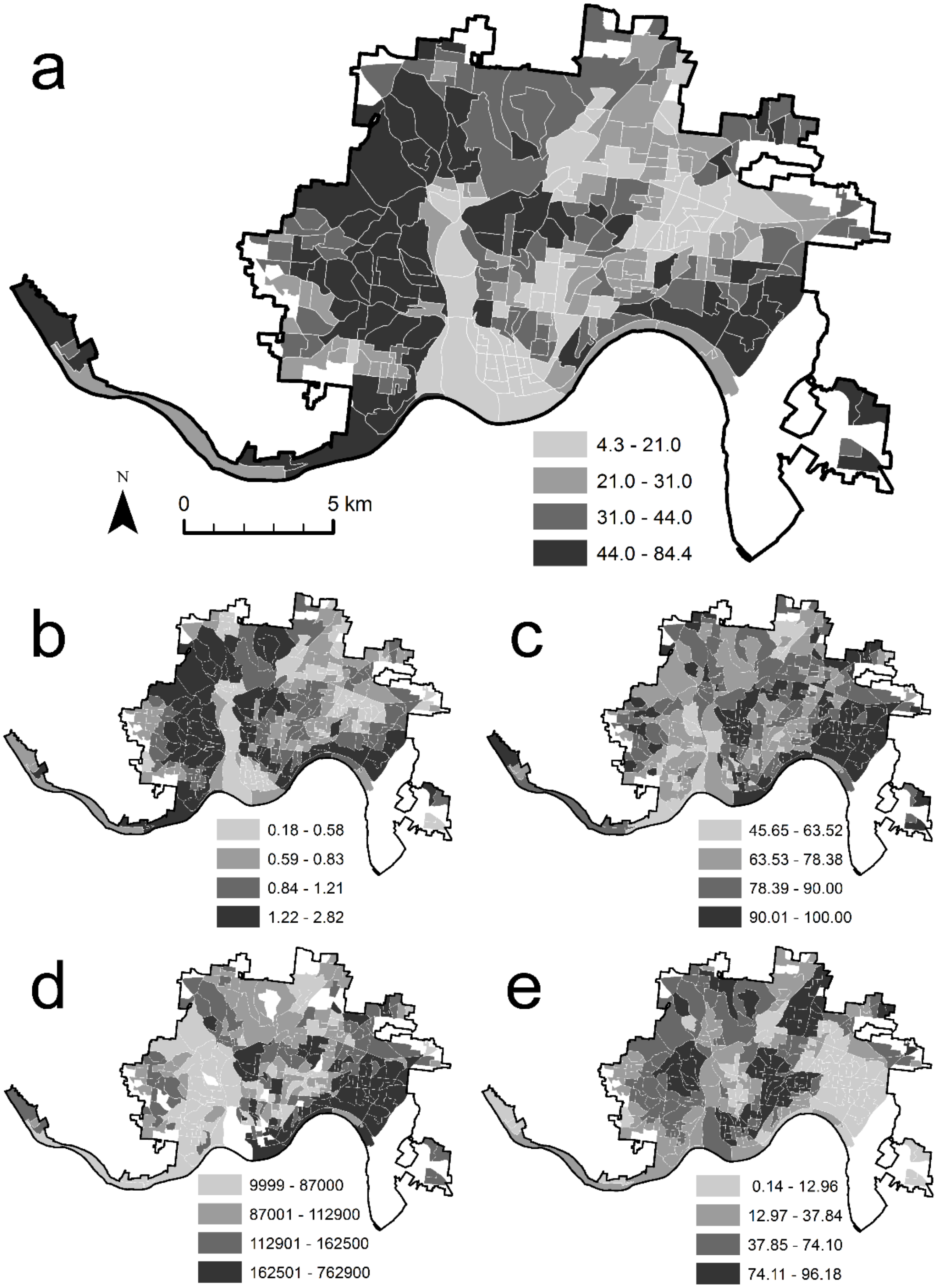


Data Collection and Preparation

Urban Tree Canopy Data

Urban tree canopy data were acquired for Cincinnati for the year 2011 (Midwest UTC 2011). These data were created using geographic object-based image analysis of 4-band (RGB + CIR) orthophotos resampled from 0.15 m (6 in) to 0.61 m (2 ft) resolution (Midwest UTC 2011). We assessed the accuracy of the canopy cover data set by randomly distributing 500 points across Cincinnati and making canopy/no canopy observations at those points using high-resolution orthophotos. We then compared our observations to the tree canopy classification; overall assessed accuracy was 93%. We summarized the tree canopy data as the proportion of each census block group covered by tree canopy (Figure 2a). Census block groups were chosen as the scale of analysis because it was the finest scale at which census data were available.

Figure 2. Block group quartile maps displaying (a) percent tree canopy cover, (b) terrain index, (c) high school graduation rate (%), (d) median home value in dollars, and (e) percent black population.



Socioeconomic Data

We acquired demographic data in spatial format from the US Census Bureau's TIGER/Line data set (US Census Bureau 2011b). We selected 2011 data to match the year of the tree canopy data, and these data represent 5-year estimates from the 2007-2011 American Community Survey. We compiled the following variables of interest at the block group level: median home value, percent black or African American, and percent of individuals age 25 and over with a high school degree (Table 1). We used percent black population to indicate race because black is the primary minority group in Cincinnati, and white and black together make up 94.7% of the total population (US Census Bureau 2011a). We chose median home value as an indicator of wealth rather than median household income, because the home is a physical manifestation of wealth that is situated geographically alongside tree canopy. Median home values were natural log transformed to meet the assumption of normality for statistical analysis. Finally, we used the high school graduation rate to indicate education because this factor is closely related to other measures of education and has been used in similar studies (e.g., Troy et al. 2007; Lowry et al. 2012). We did not include some variables that have been found to be significant in other papers investigating the distribution of urban tree cover. For example, housing age has been associated with tree canopy cover because trees take time to mature following construction (Grove et al. 2006; Berland 2012). However, we excluded this variable because 97.5% of Cincinnati block groups had a mean housing construction date before 1965, which is long enough for the effects of lagged tree growth to dissipate (Roman and Scatena 2011; Berland and Hopton 2014).

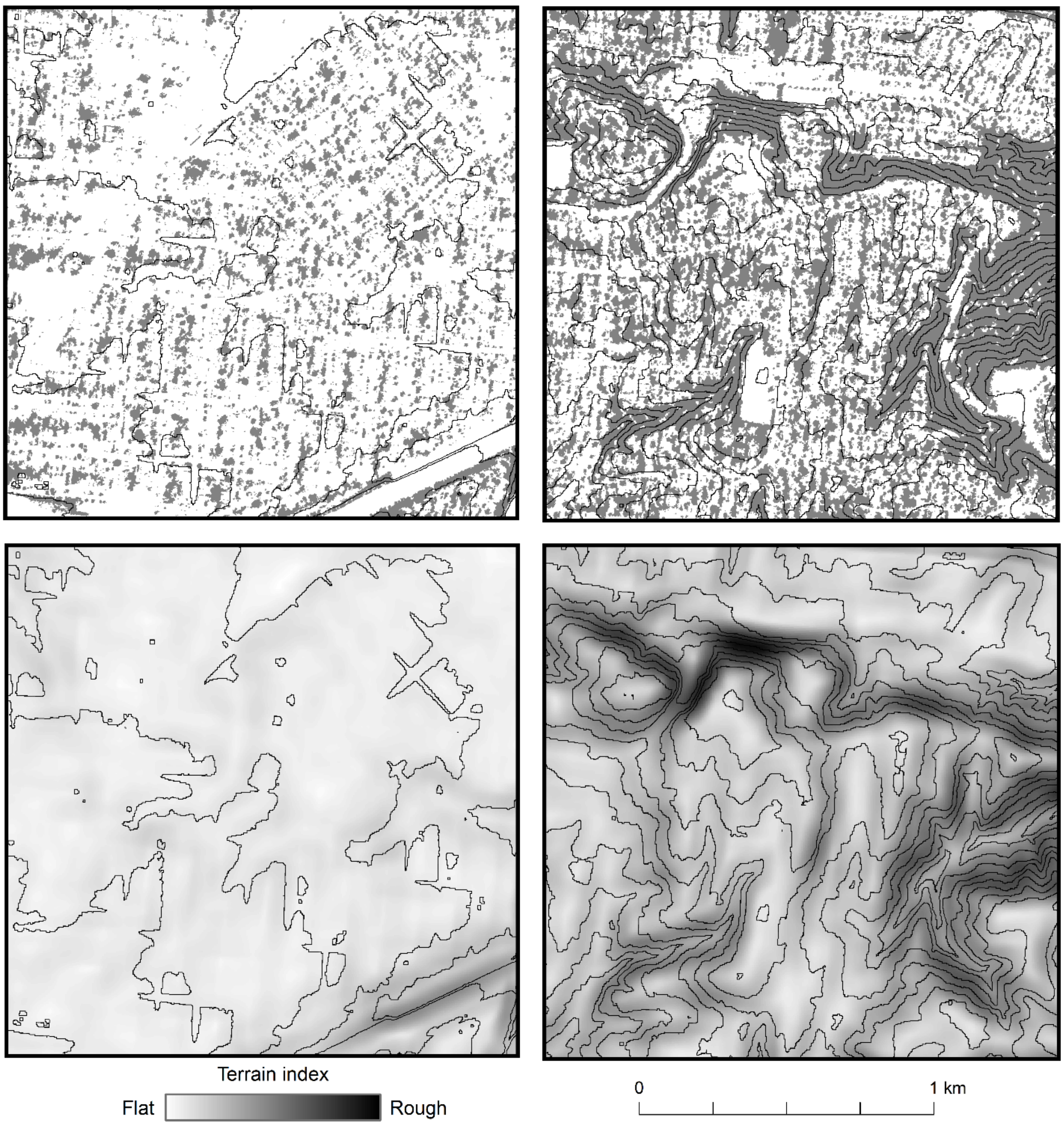
Table 1. Data summary for Cincinnati block groups (*n*=285).

Variable	Minimum	Maximum	Mean	Standard deviation
Tree canopy cover (%), all land	4.3	84.4	32.6	16.6
Tree canopy cover (%), residential land only	0.5	86.0	41.0	15.4
Terrain index	0.18	2.82	0.96	0.49
Median home value ($)	9,999	762,900	144,881	102,809
Black population (% of total)	0.1	96.2	43.4	32.0
High school graduation rate (%)	45.7	100.0	81.9	12.7

Terrain Data

In this study, we use the term terrain to describe variability in land surface elevation. We developed a terrain index based on a 3-meter resolution digital elevation model from the National Elevation Dataset (Gesch et al. 2002). Specifically, we calculated the standard deviation of elevation values within a 10x10-pixel moving window. Thus, highly variable or rough terrain is represented by high terrain index values (Figure 3). We selected a 10x10-pixel moving window to capture fine-scale variations in terrain at approximately the scale of individual property parcels. We summarized the terrain index as the mean block group value to match the scale at which socioeconomic variables were reported (Figure 2b). Note that this terrain index is highly correlated with alternative terrain calculations computed at finer or coarser moving window sizes and based on elevation ranges, indicating this index offers a robust description of topographic variability. The terrain index was natural log transformed to meet the assumption of normality for statistical analysis.

Figure 3. Examples highlighting the strong relationship between terrain and tree canopy cover. The top panels compare tree canopy cover (gray) in a relatively flat area (left, 19.1% canopy cover) vs. an area with relatively rough terrain (right, 48.9% canopy cover). The bottom panels depict the terrain index for the same areas. Contour lines on all images represent 5 m elevation changes. Both areas are primarily residential and are shown at 1:8,000 scale.



Data Analysis

All block groups with at least 95% of their total area within Cincinnati were retained for analysis (*n*=285; Figure 1). This ensured that estimates of tree canopy cover, which were limited to Cincinnati only, were representative of broader tree canopy patterns in the block group. Eighteen block groups were missing values for one or more of the variables and were excluded from analysis. The core of the analysis was a multivariate linear regression of the relationship between canopy cover percentage and the independent variables (terrain, median home value, percent black, and high school graduation rate) that accounts for spatial autocorrelation. We constructed two separate models to account for land use in the block groups. The first model assessed tree canopy cover on all land, with the expectation that block group residents would experience the amenities provided by canopy cover no matter where in the block group the canopy cover was located. The second model only considered tree canopy cover on residential land, which may more accurately reflect resident access to canopy cover in hilly block groups where trees may be inaccessible because they are concentrated on steep slopes on nonresidential land. Residential land was delineated using Hamilton County parcel data (CAGIS 2014).

Prior to running the regression models, we determined whether independent variables should be excluded from analysis due to excessive multicollinearity. We examined variance inflation factors (VIFs) of an ordinary least squares regression performed in JMP version 11 (SAS Institute 2013); all variables had low VIFs (<2). We also ran Pearson correlations in JMP to check for multicollinearity. The threshold to exclude a variable was a Pearson correlation coefficient between two variables of 0.7 or higher (Dormann et al. 2013). All Pearson correlation coefficients were less than 0.7, but there were statistically significant correlations among the socioeconomic variables (Table 2). Based on these results, all independent variables were retained in the multivariate regression.

Initially, we performed ordinary least squares (OLS) regressions to explain tree canopy cover. Evaluation of the OLS regression models using Moran's I indicated substantial spatial autocorrelation in the residuals for models including all land ($I = 0.53$) and residential land only ($I = 0.51$), which violates the model's assumption of independent observations. To address the issue of spatial autocorrelation, we implemented a spatial autoregressive model using GeoDa version 1.4.6 (Anselin et al. 2006). We chose a spatial lag model, as opposed to a spatial error model, based on the expectation that the dependent variable values for a block group were functionally related to the values of their neighbors (Anselin 2001). We created a spatial weight matrix to account for spatial relationships with queen contiguity spatial weighting, which accounts for the value of all neighboring census block groups that share a boundary with a given block group. In the spatial autoregressive model, independent variables were considered significant when p was less than 0.05.

Table 2. Pearson correlation coefficients for independent variables. Abbreviations are MHV for median home value, % Black for the percentage of total population that identifies as black or African American, and % HS Grad for the percentage of the population age 25 and over that has graduated from high school. Asterisks (*) denote $p < 0.05$.

Variable	MHV	% Black	% HS Grad
Terrain index	-0.02	-0.03	0.02
Median home value ($)		-0.38*	0.58*
Black population (% of total)			-0.36*

RESULTS

We observed substantial variability in tree canopy cover, terrain, and socioeconomics at the block group scale (Table 1, Figure 2). Mean tree canopy cover was greater than 32%, and ranged from nearly absent (4.3%) to approaching complete cover (84.4%) (Table 1). Block group terrain and the socioeconomic variables also exhibited sharp differences; for example, percent black population varied from 0.1% to 96.2% (Table 1). Visual inspection indicates spatial clustering of similar values for each variable (Figure 2). The arrangement of these clusters appears to be related, at least in part, to the locations of major waterways in Cincinnati (see Figure 1). This is especially true for the terrain index (Figure 2b), as waterways are a strong determinant of topography (Lerch et al. 1982). There are the *western hills* that surround Mill Creek and extend along the western finger of the Ohio River. There are the *eastern hills* that abut the Ohio River to the south and the Little Miami River to the east. Finally, there are the *central flatlands* situated between the two hillier regions described.

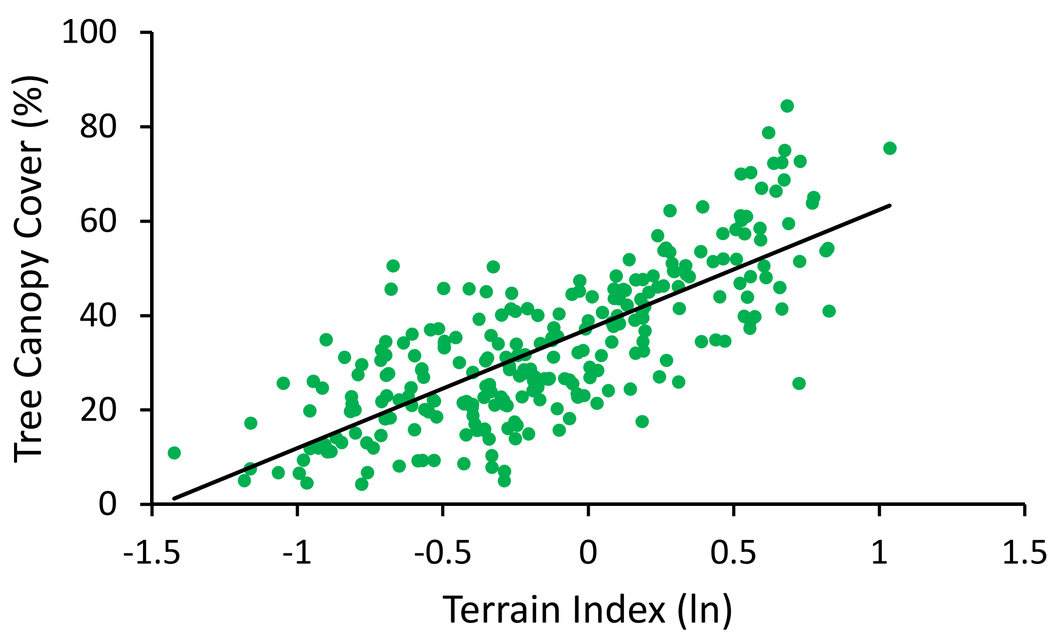
Pearson correlations revealed significant relationships among the socioeconomic variables (Table 2). This included a positive relationship between median home value and high school graduation rate, and negative correlations between percent black and both median home value and high school graduation rate. The strongest correlation was between median home value and high school graduation at 0.58. There were no significant correlations between terrain and the three socioeconomic variables (Table 2).

We modeled tree canopy cover as a function of terrain and socioeconomic variables, with an additional variable – the spatial lag weighted matrix – included to account for spatial autocorrelation. For the model including all land in each block group, the weighted matrix was effective in accounting for spatial autocorrelation, as residual Moran's *I* was reduced from 0.53 in the OLS regression to 0.14 in the spatial autoregressive model. Terrain was the dominant predictor of tree canopy cover with rougher terrain predicting greater levels of canopy cover (Table 3). No socioeconomic variables were statistically significant. Because terrain was the only significant variable to explain tree canopy cover, we conducted an OLS regression of percent canopy as a function of terrain (natural log) to visualize this relationship. There was a strong fit (R^2=0.59; Figure 4). Our analysis is potentially limited by restricting analysis to a single scale, and we addressed this by conducting an exploratory analysis of the relationship between canopy cover and terrain at the finer scale of census blocks. The relationship was still strong at the block scale (R^2=0.32; p<0.001), supporting our finding of a close association between terrain and canopy cover. However, census socioeconomic variables were not available at the block scale so we could not construct a full model.

Table 3. Results of spatial autoregressive models explaining percent tree canopy cover. We conducted separate analyses for all land and for residential land only. Significant variables (p<0.05) are in bold.

Source	Coefficient	SE	*z*-score	*p*-value
All land				
Spatial lag weighted variable	0.47	0.05	9.19	<0.001
Constant	4.81	12.33	0.39	0.696
Terrain index	**18.78**	**1.38**	**13.61**	**<0.001**
Median home value ($)	0.55	1.16	0.48	0.634
Black population (% of total)	0.02	0.02	0.91	0.362
High school graduation rate (%)	0.10	0.05	1.90	0.058
Residential land only				
Spatial lag weighted variable	0.58	0.05	12.36	<0.001
Constant	-10.65	11.69	-0.91	0.362
Terrain index	**14.97**	**1.27**	**11.83**	**<0.001**
Median home value ($)	**2.19**	**1.10**	**1.99**	**0.047**
Black population (% of total)	**0.04**	**0.02**	**1.98**	**0.047**
High school graduation rate (%)	0.03	0.05	0.64	0.525

Figure 4. Bivariate analysis of tree canopy cover as a function of terrain, including ordinary least squares regression line (R^2 = 0.59). Points represent census block groups.



In the model for residential land only, the spatial lag weighted matrix was again successful in accounting for spatial autocorrelation, as residual Moran's *I* was reduced from 0.51 in the OLS regression to 0.08. Similar to the model for all land, terrain was a dominant and positive predictor of tree canopy cover on residential land (Table 3). In this model, home value (p=0.047) and percent black (p=0.047) were also significant, positive independent variables.

DISCUSSION

The overarching goal of this paper was to highlight the potential role that local biogeophysical context plays in modifying expected environmental justice patterns regarding the distribution of an environmental amenity. We showed that terrain plays a significant role in explaining the distribution of tree canopy cover in Cincinnati. The results have implications for management and policy surrounding urban tree cover and sustainability goals in Cincinnati, but perhaps more importantly, they emphasize the need for the socio-ecological community to ground equity research in the context of place – in other words, place matters.

How Place Matters in Cincinnati

In both spatial autoregressive models, terrain was the dominant predictor of tree canopy cover (Table 3). The results of our simple linear regression attest to the importance of terrain for explaining tree canopy cover, with nearly 60% of the variation in the data explained by the terrain index (Figure 4). Such a strong biogeophysical explanatory variable for tree canopy cover may mask subtler relationships among tree canopy and socioeconomic variables. The heterogeneous terrain in Cincinnati can be seen in the previously described western hills, eastern hills, and central flatlands (Figure 2b). Both the western hills and the eastern hills have high tree canopy cover (Figure 2a); however, they exhibit different socioeconomic characteristics. Lower median home values (Figure 2d) and a higher percentage of the population that identifies as black or African American (Figure 2e) are spatially aligned along the western hills. On the eastern hills, median home values are higher and a larger percentage of the population identifies as white.

Our statistical model for residential land only identified both percent black and median home value as positive predictors of tree canopy (Table 3), reflecting the high levels of tree canopy cover on both western and eastern hills. These marked geographic patterns represent a historical legacy of earlier segregation processes that shaped Cincinnati's neighborhood structure according to race and wealth. According to Taylor (1984), the city's terrain largely dictated historical patterns of land use and separated wealthy whites from black and poor white populations. So while we did not explicitly account for these historical legacies in our study, their effects are evident in contemporary patterns of tree canopy cover on residential land. That is, tree canopy cover is positively associated with higher black populations and higher median home values that are spatially segregated on western and eastern hills, respectively. Our findings are consistent with the idea that past decisions that segregated wealthy whites from black and poor white populations in two different hilly areas led to high tree canopy cover in both areas simply because terrain is a primary factor influencing canopy cover in Cincinnati.

The Importance of Place in Urban Tree Planting Decisions

Our results have important implications for urban tree planting decisions. Tree canopy cover at the municipal level is often actively created and maintained through tree planting initiatives (e.g., McPherson et al. 2011). Tree planting decisions may be influenced by multiple factors including a normative goal to increase canopy cover in low cover areas. Understanding the current spatial distribution of tree canopy cover is especially important for identifying low cover areas for the placement of trees. Increasingly, planting decisions not only consider the spatial distribution of canopy cover but *who* has access to canopy cover (Danford et al. 2014). Our results demonstrate that environmental justice outcomes, however, may be modified by local biogeophysical context. A citywide analysis of Cincinnati revealed equal distributions of tree canopy cover; that is, citywide canopy cover was not unevenly distributed at the block group scale with regards to race, home value, or educational attainment. Instead, terrain relates to tree canopy cover such that areas with more topographic variability have higher tree cover. Correlations between the social structure of the city and tree canopy cover are either weak or they are masked by a dominant biogeophysical factor influencing canopy cover. The pattern was different when only residential land is considered, as canopy was positively associated with percent black and median home values. However, these socioeconomic factors were substantially weaker predictors of tree canopy cover than terrain (Table 3). Given the importance of terrain in our models, it is essential to understand the role of terrain in canopy cover and environmental justice outcomes in order to advance urban sustainability goals through tree cover in Cincinnati.

Equal, but Not Necessarily Just

Although one may argue that our analysis of all land demonstrates a city with equal distributions of tree canopy cover (Table 3), equal does not necessarily mean just. Not all canopy cover is the same, as some species and some types of urban forest structure are more desirable than others. In other words, the quantity of canopy cover may not fully reflect the quality (Kenney et al. 2011), and furthermore, quality is subject to human preference and context. Canopy cover may not reflect the preferences of current residents due to a mismatch in timescales between neighborhood demographics and the life cycle of trees (Boone et al. 2010). In addition, remotely sensed canopy cover obscures both maintenance regimes and intentionality in temperate cities because trees can grow on unmanaged land without water subsidies (Schwarz et al. in review). In contrast, tree cover may more accurately reflect maintenance and investment in arid cities where water subsidies are required (Schwarz et al. in review). These contrasts have important implications because unintentional and unmaintained trees in temperate cities may be more likely considered a disamenity (e.g., invasive species volunteering on abandoned properties), with geographic context tipping the balance between an environmental good and bad. In summary, our analysis is valuable because canopy cover is a primary urban forest metric used for benchmarking and planning, but additional research is needed to understand urban forest characteristics beyond canopy cover (e.g., species composition, management regimes), and how diverse residents value urban forest resources and attendant environmental amenities.

The Need for Place-Based Environmental Justice Research

Many variables can influence the social and biogeophysical templates of a city. Tree canopy cover can be influenced by temperature, rainfall, length of the growing season, public or private investment and management, and in the case of Cincinnati, terrain. Likewise, the social structure of a city is influenced by numerous factors including power, politics, religion, and money. In Cincinnati, past land use decisions and discriminatory real estate practices that steered black and poor populations toward specific neighborhoods contributed to the current pattern of racial and economic segregation (Taylor 1984). Legacies of these past phenomena remain evident on today's landscape, and these legacies influence our interpretation of contemporary tree canopy cover. Convergence of the social and biogeophysical templates is place dependent, and recognizing the resulting unique socio-ecological structure can help cities advance urban sustainability goals by managing tree canopy cover and associated ecosystem services in an equitable and just manner. Overlaying these social and biogeophysical templates is a first step in achieving urban sustainability goals, and one that gets us closer to understanding the processes that influence the spatial distribution of environmental amenities.

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