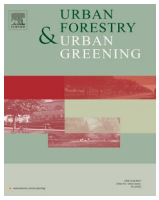
Urban Forestry & Urban Greening 113 (2025) 129105

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug



Baltimore street tree distribution and condition relate to socioeconomic factors, while tree diversity and size relate to neighborhood environmental conditions

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ARTICLE INFO

Keywords:
Beta diversity
Community composition
Socioeconomic status
Species diversity
Street trees
Urban tree health
Urban forestry

ABSTRACT

Street tree diversity and distribution are often associated with socioeconomic factors like race and income, but distribution of planting sites, street tree condition, and more nuanced biodiversity metrics such as evenness and beta diversity have been less well studied. Motivated by previous findings that street tree communities reflect historical redlining practices, we examined the relationship between present-day socio-environmental characteristics and street tree diversity, condition, and stocking levels in neighborhoods of Baltimore, Maryland, USA. Street tree stocking rates were positively associated with percent White population, income, and educational attainment, and negatively associated with percent Black population. Neighborhoods with more impervious surface cover and hotter air temperatures also had smaller trees, lower species richness and evenness, and a lower percentage of planting sites meeting the Baltimore City Forestry Division's target size. Neighborhoods with higher air temperatures had more similar street tree community composition. Air temperature, income, race, and educational attainment were all significant factors differentiating street tree community composition. Trees in poor and dead condition were positively correlated with percent Black population, while trees in good condition were positively correlated with percent White population, income, and educational attainment. Results demonstrate that the distribution and quality of Baltimore's street trees are associated with social and environmental factors. Socioeconomic factors are more strongly associated with street tree stocking and condition, while environmental factors are correlated with street tree diversity and size. These results may inform urban natural resource management to achieve equitable distribution of street trees and related ecosystem services across the city's neighborhoods.

1. Introduction

Since the late 19th century, street trees have played a central role in urban beautification efforts in the United States (Seamans, 2013). Typically located in the public right-of-way, street trees have remained a key focus of municipal urban forestry operations since the establishment of urban forestry as a formal discipline in the 1970s and 1980s. Recognized as critical green infrastructure, street trees provide key ecological, social, and cultural benefits to cities (Seamans, 2013) and play a vital role in mitigating many of the harmful conditions associated with living in an urban area. For example, street trees mitigate the urban heat island effect by reducing air temperature and providing shade (Bowler et al., 2010; Salmond et al., 2016; Locke et al., 2024) and mitigate flooding by increasing storm water retention (Escobedo et al., 2011; Ponte et al., 2021). Additionally, street trees provide noise barriers by diminishing sounds from urban traffic (Tallis et al., 2011) and urban fauna rely on street trees as habitat and passageways between patches of vegetation (Mullaney et al., 2015). Among urban tree site types (e.g., residential yard trees, park trees, etc.), street trees are particularly subject to human intervention; their planting and removal can reflect stewardship activity and political agendas from citywide to local community levels (Carmichael and McDonough, 2019; Young,

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https://doi.org/10.1016/j.ufug.2025.129105
Received 19 November 2024; Received in revised form 15 August 2025; Accepted 4 October 2025
Available online 6 October 2025

2010).

Municipal street tree inventories to monitor and manage this important natural resource have been growing in prevalence (Ma et al. 2021), allowing for comprehensive analysis of urban street tree population characteristics. These data allow urban foresters to assess whether street tree populations are meeting diversity goals at taxonomic family, genus, and species levels (Santamour, 1990; Kendal et al., 2014). For example, the 10–20–30 rule recommends that no more than 10 % of trees in a city should belong to a single species, no more than 20 % should belong to a single genus, and no more than 30 % should belong to a single family (Galle et al., 2021; Santamour, 1990). This benchmark aims to enhance the resilience and ecological benefits of urban forests by encouraging a balanced distribution of tree species (Galle et al., 2021). Greater species diversity increases the resilience of urban tree populations against pests and diseases (Morgenroth et al., 2016). In addition, more attention should be paid to variation in street tree condition across urban neighborhoods since many benefits and ecosystem services are derived from large and healthy trees (Mullaney et al., 2015). While a neighborhood may contain a large quantity of street trees, the trees may be in poor condition and/or small, with restricted growth due to limited soil volume or other biophysical constraints. For example, one study from Washington, D.C. found a negative relationship between median household income and the percent of street trees under stress, and a positive relationship between extreme summer temperature and percent of street trees under stress (Fang et al., 2023). Thus, given the important role of street trees in mitigating urban stressors and environmental vulnerability, there is the need to better understand the distribution and correlates of street tree diversity and condition within cities.

Despite the numerous benefits trees provide, street trees are often unevenly distributed within an urban environment, resulting in variation in the distribution of benefits to urban residents. Previous studies have found that race, income, and education are closely related to street tree distribution across geographic areas in New York City (Lin et al., 2021) and Barcelona (Padullés Cubino and Retana, 2023). For example, the study conducted in New York City found fewer street trees and lower species diversity in areas with a higher proportion of racial minorities and those with lower rates of formal education (Lin et al., 2021). Similarly, studies from Montreal, Canada have found that street tree cover is positively associated with population density, median housing value, and educational attainment, but negatively correlated with percent of recent immigrant residents (Pham et al. 2013, 2017). Finally, street tree abundance in Houston, Texas was found to be positively associated with median housing value and negatively associated with percent renter occupied housing (Lin and Güneralp, 2024).v

Baltimore, MD is a majority Black city with a declining population and has been the subject of in-depth urban ecology research for many decades (Grove et al. 2024). An analysis of multiple tree inventories from Baltimore, MD found that street trees contribute significantly to total urban forest species richness and biomass, and that species richness and biomass added by street trees are positively correlated with household income (Anderson et al., 2023). Historical legacies of public policy may further exacerbate disparities, as evidenced by another study comparing current Baltimore street tree diversity across neighborhoods assigned to different 1937 home-owner loan corporation (HOLC) categories (i.e., redlining) (Burghardt et al., 2022). The study found that formerly redlined neighborhoods typically contain lower tree species diversity and fewer larger (and presumably older) trees, suggesting a historical lack of investment and/or harsh growing conditions in these neighborhoods. This analysis also found a higher prevalence of smaller trees in these once redlined neighborhoods, displaying evidence of recent investment in tree plantings. This study garnered attention from Baltimore's municipal and non-profit forestry organizations who actively work to address patterns of historical environmental inequity (Sonti et al. 2024). These urban forestry practitioners identified the strengths and limitations of the analysis of historical HOLC-defined neighborhoods and identified a need to expand these detailed analyses of tree quality, diversity and community composition to the entire present-day geography of Baltimore City neighborhoods (Sonti et al., 2024). Building upon existing research examining the distribution and diversity of street tree populations, our study expands the scope of analysis to include considerations of street tree and planting site conditions alongside multiple dimensions of species diversity (e.g., species richness, evenness and beta diversity). Different aspects of biodiversity capture patterns of species distribution and composition that can affect street tree community resilience and ecosystem services provided to local residents. Additional street tree characteristics such as tree condition and planting site dimensions can suggest neighborhoods where interventions may be needed to enhance tree health or available planting space, as well as communicate with residents about these interventions.

Our study evaluates demographic, economic, and environmental factors as correlates of street tree attributes at the neighborhood level in Baltimore, MD. We intentionally chose to use simple bivariate correlations in our study in order to address practitioner needs to identify existing relationships between street tree community characteristics and neighborhood socio-environmental variables. Other more statistically complex approaches may combine several autocorrelated socio-environmental variables into indices to predict street tree outcomes (see Keller et al., 2024; Martin et al., 2025). However, we wanted to use the socioeconomic and environmental variables that were of interest to local urban foresters and readily interpretable by practitioners and policymakers when summarized to the neighborhood scale. We recognize the limitations of bivariate correlations and do not claim to identify the predictors or drivers of street tree community characteristics. However, we are able to identify relationships that exist on the ground across Baltimore City neighborhoods and that are experienced by local residents.

We aim to answer the following question: How do neighborhood social and environmental characteristics relate to street tree distribution, condition, and diversity? Given historical disinvestment in Baltimore communities (Grove et al., 2018; Brown, 2021), we hypothesize that neighborhoods with higher proportions of Black residents, low-income residents, and residents with lower educational attainment will demonstrate: lower street tree species diversity, lower street tree stocking levels, and a greater proportion of street trees in poor condition. We predict that neighborhoods with higher afternoon air temperatures and greater percent impervious surface cover will also demonstrate lower street tree species diversity, lower street tree stocking levels, and a greater proportion of street trees in poor condition, as well as lower average tree DBH (diameter at 1.35 m) and a lower percentage of sites meeting target tree pit size.

2. Materials and methods

2.1. Study area

The City of Baltimore is located in the Chesapeake Bay region of the United States. It is the largest city in Maryland with a population of 585,708 people (United States Census Bureau, 2020). It is jurisdictionally distinct from neighboring Baltimore County and does not overlap territorially. The region features Piedmont and coastal plain geology and ecologically is an eastern deciduous forest in a temperate climate (Anderson et al., 2023). The city's population has declined since its peak of almost 950,000 in 1950; today there are at least 17,000 vacant lots and additional vacant buildings (Locke et al., 2023). Baltimore is a majority Black city, with 58 % Black and 28 % White residents as of 2020 (United States Census Bureau, 2020). Patterns of racial segregation in Baltimore's neighborhoods have been described by Brown (2021) as the "White L" and the "Black Butterfly" where the predominantly White neighborhoods cluster along a north-south rib, and an east-west line from the inner harbor eastward resembling the letter "L". Concurrently predominantly Black neighborhoods cluster in East and West Baltimore

in mirror image of each other, hence the "Black Butterfly" (see Fig. S1A, B).

Baltimore City's street trees are largely planted, maintained, removed, and recycled by the Department of Recreation & Parks' Forestry Division. Planting and stewardship activities are coordinated through the Forestry Division's TreeBaltimore program (BCRP, 2007), which is a mayoral initiative to expand the city's tree canopy cover through the establishment, management, and preservation of trees. Serving as an umbrella organization for all city agencies, private organizations, and individuals working towards this goal, TreeBaltimore supports local groups like Baltimore Tree Trust and Blue Water Baltimore. These groups receive free trees to plant and establish on public and private property in neighborhoods throughout the city. Private developers, businesses, and institutional property owners (or contractors working on their behalf) may also plant approved street tree species following a permit acquisition process.

2.2. Neighborhood socio-environmental data

For our study, socio-environmental and street tree variables are summarized into neighborhoods to provide meaningful units of analysis. Baltimore City is divided into 56 neighborhoods, defined as Community Statistical Areas (CSA) by the Baltimore Neighborhood Indicators Alliance (BNIA; https://bniajfi.org/), an organization that aggregates data from government agencies, nonprofit organizations, academic institutions, and other sources on a variety of topics relating to community well-being in Baltimore. Socioeconomic and demographic data were also obtained from BNIA, which calculated these variables using the 2020 census block groups and CSA boundaries. Census block groups cleanly correspond to CSA boundaries (block groups are never divided by CSA), so CSA-level variables were derived from the block group values in that CSA. As an example, BNIA calculated percent Black at the CSA level by summing the population of all block groups in that CSA, summing the Black population in that CSA, and then dividing the sum of the Black population by the sum of the total population. We chose five neighborhood socioeconomic variables based on their use in prior studies of urban forest structure (Troy et al., 2007, Landry & Chakraborty, 2009; Pham et al., 2017): percent Black population, percent White population, median household income, percent of residents over 25 with a Bachelor's degree or higher (educational attainment), and percentage of vacant and abandoned residential properties (vacancy).

We included three additional neighborhood environmental variables: afternoon air temperature, impervious surface cover, and summed road lengths. Average afternoon neighborhood temperature captures extreme urban heat that could be mitigated by shade-providing street trees (Shandas et al., 2019). Baltimore afternoon temperature data were acquired from the National Oceanic and Atmospheric Administration (Shandas et al., 2019; CAPA/NIHHIS and Boyce, 2023). The data were a raster surface file of modeled afternoon (3 PM) ambient temperature. Average afternoon temperature was calculated for each neighborhood by averaging pixel values in that neighborhood from the raster surface. Percent impervious surface cover per neighborhood was calculated by intersecting neighborhoods with high resolution land cover data from the Chesapeake Conservancy (Chesapeake Bay Program, 2022; Pallai and Wesson, 2017). Total road length per neighborhood was calculated by intersecting neighborhoods with the Maryland Department of Transportation's Know Your Roads layer (https://data.imap.maryland.gov/datasets/mdot-know-your-roads/about), and then summing total road length per neighborhood.

2.3. Street tree data

Street tree data were acquired from the Baltimore City Department of Recreation & Parks Forestry Division. The city hired independent contractors to collect information about every street tree and maintained park tree during 2017 and 2018. For the purposes of this analysis, all park trees were removed from the dataset using the location type attribute field in the database that indicated "Street" or "Park". The dataset contains street address, latitude, longitude, species, condition, and planting space type and size for all live street trees, dead street trees, and importantly, potential street tree sites in Baltimore (BCRP, 2021). Potential tree sites were identified in areas where a street tree could be put into place. The street tree dataset was spatially joined to corresponding neighborhoods. Two outlier neighborhoods, Dickeyville/Franklintown and Unassigned Jail, were excluded as they had significantly fewer street trees than the other neighborhoods, resulting in a total of 54 neighborhoods included in our analyses. Dickeyville/Franklintown contains Gwynns Falls / Leakin Park, a large city-owned park that covers most of the neighborhood's area. The Unassigned Jail neighborhood contains a mix of city- and state-owned facilities that take up most of that neighborhood's area. Dickeyville/Franklintown contained 74 street trees, and Unassigned Jail contained 162 trees, or 0.045 % and 0.099 % of the street tree dataset, respectively. The average number of trees per neighborhood was 2870.

2.4. Street tree variables

2.4.1. Distribution

Our study utilizes total plantable street tree sites (referred to as potential tree sites) and street tree stocking to investigate differences in street tree distribution among Baltimore neighborhoods. The total number of street tree sites in each neighborhood includes sites with living trees, dead trees, tree stumps, vacant street tree sites, and potential sites where tree pits could be made. Potential sites were identified based on brief site inspections, and may not be plantable once utility lines or other infrastructure conflicts are accounted for. We calculated stocking rate as the number of live street trees divided by the total number of street tree sites within a neighborhood. Trees and shrubs of unknown species and trees only identified to the genus level were used to calculate the street tree stocking rate but were removed for diversity measures. In addition to the number of street tree sites, our study investigates the size of tree planting sites in a neighborhood. To do this, the tree planting site area was compared to a target planting space size of 3 m^2 (32 ft^2), which is the minimum size required for new tree pit construction currently used by Baltimore City's Forestry Division (City of Baltimore, 2019). Larger planting sites allow for more water infiltration and rooting space and therefore allow for greater growth potential (Sanders et al., 2013). We calculated the percentage of planting sites that were greater than or equal to 3 m^2 (hereafter target pit size) using the planting space dimensions provided in the street tree inventory. Large planting spaces (typically lawn planting strips or unrestricted space types) were given a length and/or width of "> 20 ft" in the inventory. For these trees, we assumed length and/or width of 6.1 m (20.01 ft) to calculate the planting space area. Only sixteen planting sites out of the entire dataset had a length and/or width of "> 20 ft" and did not meet the target pit size of 3 m^2, which means that while the actual planting site lengths and/or widths are likely greater, this would not impact the results of our target pit size analysis.

2.4.2. Species diversity and composition

Species evenness (measured using evar) was calculated using the CoDyn R package using community_structure() (Hallett et al., 2020). Species richness was rarefied to account for the different number of trees in each neighborhood using rarefy() from the vegan R package (Oksanen et al., 2022). All samples were rarefield to 453 trees, the fewest number of trees found in a neighborhood; hereafter rarefied richness is simply termed richness. We also assessed whether each neighborhood met the 10–20–30 rule as well as a 5–10–15 benchmark, which follows the same guidelines as the 10–20–30 rule but with stricter parameters (Ma et al., 2020; Galle et al., 2021). Each tree species was classified as either a small or a large stature tree (Hughes et al. 2015). For example, eastern redbud (*Cercis canadensis*) was considered a small stature tree and white

oak (*Quercus alba*) a large stature tree. We then calculated the average DBH of large and small stature trees separately in each neighborhood. While species richness and evenness are important descriptors of community diversity, they distill complex community composition data (which species are present and their associated abundance) to a single univariate measure. Multivariate analyses can enable the study of the community composition (Avolio et al., 2022). Beta diversity is a measure of the similarity in species composition. We took two approaches to assessing beta diversity. First, we assessed beta diversity within neighborhoods by calculating street tree species differences (Baselga, 2013) among all streets in a neighborhood using the RAC_difference function (Avolio et al., 2019) in the CoDyn R Package. Next, we asked whether neighborhoods with similar demographic characteristics had similar tree communities. For this analysis, we first summed the total number of trees of each species within a neighborhood, to create a single vector of composition. Next, we binned the neighborhood characteristics (race, median household income, educational attainment, air temperature, and vacancy rate) to address whether neighborhoods with similar socio-environmental characteristics also had similar street tree communities, facilitating interpretation of complex multivariate analysis of community composition. Specifically, we identified neighborhoods with a clear majority of Black or White residents; neighborhoods above or below the median household income; neighborhoods with a clear majority of residents who have a Bachelor's degree; neighborhoods above and below the average afternoon air temperature; and neighborhoods with a high vacancy rate above the citywide average (Miller and McComas, 2022) (Table 1).

For each socio-environmental variable we performed a PERMANOVA using adonis2 in the Vegan package (Oksanen et al., 2022) to test for differences in the centroids of neighborhoods with different social or environmental characteristics (e.g., do higher income neighborhoods have different street tree community composition compared with lower income neighborhoods), and betadispr in Vegan package to test for whether neighborhoods with different social or environmental characteristics differ in their dispersion around the centroid (e.g., is the composition of street trees among higher income neighborhoods more different from one another [higher dispersion = less similar composition] compared with lower income neighborhoods [lower dispersion = more similar composition]. These approaches are used for testing multivariate community composition differences with community data (Anderson, 2017). For the socio-environmental variables that were significant, we performed non-metric multidimensional scaling (NMDS) using metaMDS in the vegan package to visualize differences in community composition.

Table 1
Descriptive statistics for socio-environmental variables calculated for each neighborhood in Baltimore City.

	Min.	Median	Mean	Max.	Bins for Beta Diversity
Black population (%)	3.91	67.96	58.31	94.17	Predom. Black (> 60 %)
White population (%)	1.22	17.27	25.85	81.54	Predom. White (> 60 %)
Median household income (USD)	21,530	48,967	55,933	134,209	Low (< 49,000), High (≥ 49,000)
Bachelor's degree (%)	6.89	23.90	32.21	83.81	Higher Ed. Attainment (> 60 %), Lower Ed. Attainment (≤ 60 %)
Air temperature (°C)	33.32	34.98	34.94	36.86	> 35 C, ≤ 35 C
Vacancy (%)	0.10	3.26	6.98	31.95	Low (< 10 %), High (≥ 10 %)
Impervious surface cover (%)	27.77	58.19	60.31	96.17	

2.4.3. Tree condition

Each tree in the dataset received a rating of good, fair, or poor condition using a system developed by the International Society of Arboriculture (Davey Resource Group, 2019). Good condition refers to a visibly healthy tree with a full canopy and little damage to the branches, limbs, and trunk. Trees in fair condition have a thinning canopy and significant damage to limbs and trunk. Poor condition describes a visibly deteriorating tree with critical damage to its limbs and trunk. We calculated the percent of trees in each neighborhood in good condition and the percent in poor condition to examine street tree health. For each neighborhood we determined the percentage of trees that were in good or poor condition divided by the total number of trees in the neighborhood. Finally, we summed the number of trees that were recorded as dead or stumps and again divided that by the total number of trees to get the percentage of trees that were dead for each neighborhood.

2.5. Correlational analysis

We performed all statistical analyses in R (v4.3.2; R Core Team, 2023) using functions from the tidyverse, sf, tidylog, and mapview packages (Wickham et al., 2019; Pebesma, 2018; Elbers, 2020; Appelhans et al., 2022). The code is available at: github.com/mavolio/BaltimoreStreetTreeProject. Our study aimed to identify significant relationships between socio-environmental variables and street tree variables. The chosen metrics capture the distribution, species diversity, composition, and condition of street trees, giving us the ability to holistically evaluate their ecological and social functioning in an urban ecosystem (Fig. S2). We analyzed the data with bivariate correlations among all socio-environmental and street tree variables rather than taking a regression approach for several reasons. First, rather than establishing a causal relationship, our study acknowledges the complex relationships between multiple social factors. For example, we do not think that whether residents have a Bachelor's degree directly results in more neighborhood street trees, but instead represents and correlates with many complex socio-political factors that can lead to having more trees in a neighborhood. Second, although multiple regression was considered, with just 54 neighborhoods and 7 socio-environmental variables, degrees of freedom are few. Recommendations for the number of observations per predictor vary (Austin and Steyerberg, 2015). An empirically defensible value is $n \geq 50 + m$, where n is the number of observations and m is the number of predictors (Green, 1991), so at least 51 observations are needed for 1 predictor. Additionally, many of the chosen socio-environmental variables are correlated (i.e., race, income, and education; percent impervious surface cover and air temperature), violating the independence assumption of multiple linear regression (Fig. S3). Because these socio-environmental variables are all of local interest to urban forestry practice and policy, bivariate correlations were deemed more appropriate analytical approach. The 54 neighborhoods defined by BNIA were used in our analyses because they correspond to socially and politically meaningful geographic units, as opposed to groupings such as Census tracts. Our threshold for significance was $p < 0.05$ for all analyses. Because we conducted so many statistical tests, we corrected for multiple hypothesis testing using the Benjamini-Hochberg correction (Benjamini and Hochberg 1995), correcting for 77 comparisons using p.adust () in R (11 street tree variables and 7 socio-environmental variables).

3. Results

3.1. Street tree distribution

Street tree characteristics vary across Baltimore City's neighborhoods (Fig. 1). The overall citywide street tree stocking rate, or percentage of filled street tree sites, was 56 % and neighborhood stocking rates ranged from 28.44 % to 87.66 % (Table 2). Across all neighborhoods, the number of potential street tree sites was not correlated with any of our socio-environmental variables (Table 3) but was correlated with road length ($r = 0.36$, $p < 0.05$). Stocking rates, in contrast, had significant relationships with several of our socio-environmental variables. Street tree stocking was higher in neighborhoods with greater income, percent White population, and educational attainment, while neighborhoods with higher proportions of Black residents had lower stocking rates (Fig. 2A,B; Table 3).The neighborhood stocking map (Fig. 1A) reflects the pattern of the "White L" and the "Black Butterfly" described by Brown (2021), referring to parts of the city with high proportions of White or Black residents (Figs. S1A,B).

Seventy-seven percent of street trees across Baltimore City neighborhoods are growing in spaces that exceed the Forestry Division's target pit size of 3 m^2. Planting sites were smaller in the more densely built downtown areas and were larger in neighborhoods located further away from the city center (Fig. 1B). Target pit size was strongly negatively correlated with percent impervious surface area and air temperature and negatively correlated with percent White population and

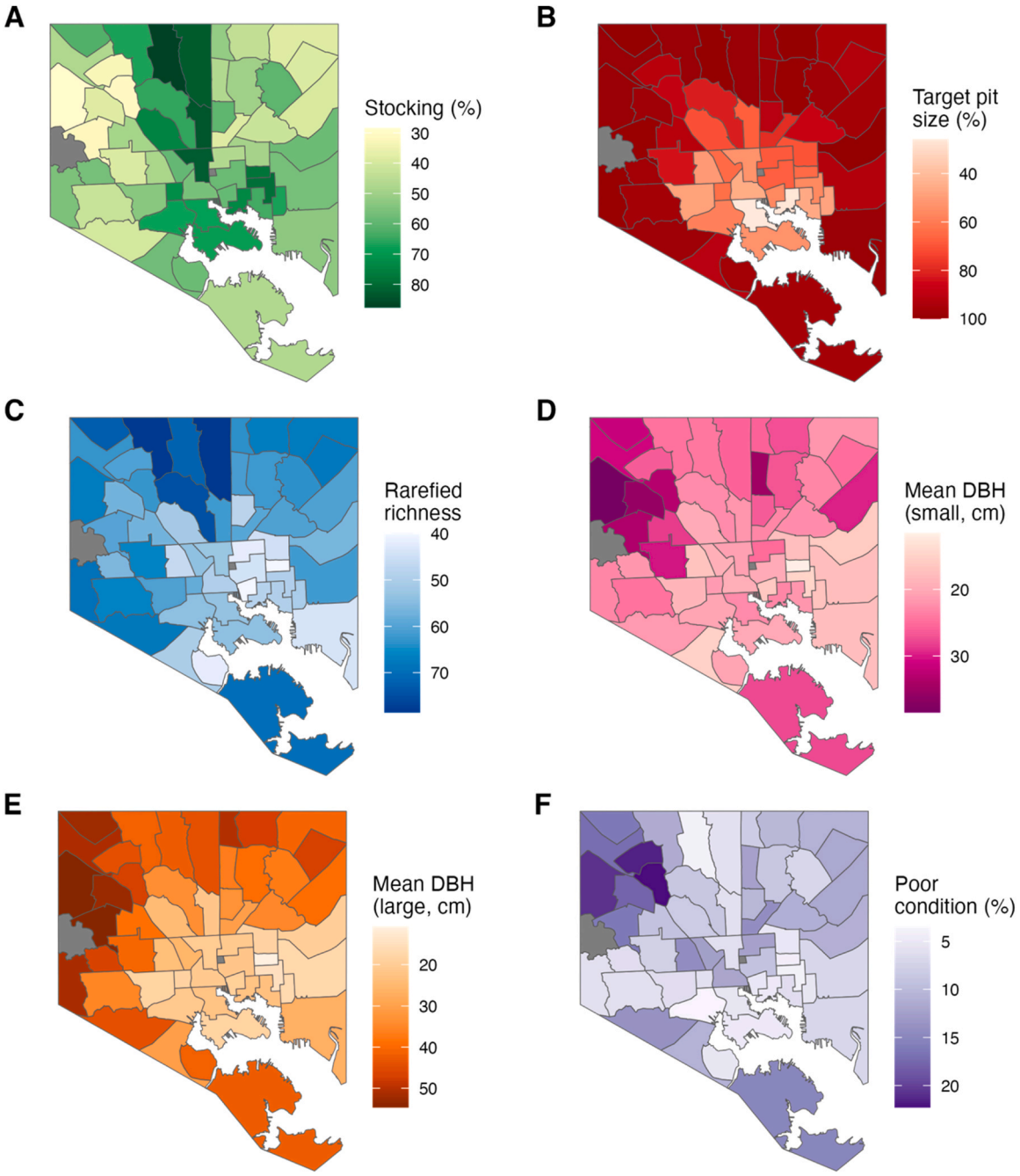

Fig. 1. Maps depicting the concentrations of: (A) stocking (percent of potential and available tree pits filled), (B) target pit size (planting sites that meet the criteria of 3 m^2 (32 ft^2), (C) rarefied species richness, (D) average DBH (diameter at breast height) of small stature trees in cm, (E) average DBH of large stature trees in cm, and (F) percent of trees in poor condition across Baltimore neighborhoods.

Table 2
Descriptive statistics for street tree variables calculated for each neighborhood in Baltimore City.

	Min	Median	Mean	Max
Potential street tree sites	784	2832	3022	6569
Stocking (%)	28.44	55.92	55.53	87.66
Sites above target pit size (%)	25.8	91.5	80.1	100
Rarefied species richness	39.9	59.5	58.1	78.6
Evenness	0.21	0.28	0.29	0.41
β Diversity	0.32	0.41	0.41	0.52
Average DBH of small species (cm)	10.9	22.4	22.9	38.3
Average DBH of large species (cm)	10.7	34.1	33.1	54.6
Poor condition (%)	3.5	8.7	9.7	22.5
Good condition (%)	31.3	63	61.1	81.8
Dead (%)	3.2	7.4	7.3	14

educational attainment (Table 3). Both large and small stature trees had smaller average DBH in hotter neighborhoods and neighborhoods with greater impervious surface area (Table 3; Fig. 2F).

3.2. Species diversity and composition

Across Baltimore there were 242 street tree species, and of these, 58 species were rare in the inventory with fewer than 5 individuals. The most common species were *Acer rubrum* (12.4 %), *Zelkova serrata* (7 %), *Tilia cordata* (5.7 %), *Platanus x acerfolia* (5.6 %), and *Prunus* spp (5.2 %). Citywide, only 8 neighborhoods meet the 10–20–30 diversity rule and all neighborhoods fail to meet the stricter 5–10–15 benchmark. 26.15 % of all trees are in the family Aceraceae (maples), 13.6 % of all trees are in the family Ulmaceae (elms), and 10.2 % are in the Fagaceae (beech and oaks). 24.7 % of all species are in the Acer genus and 10.1 % are in the Quercus genus.

Species richness demonstrated a strong negative relationship with impervious surface area and air temperature, and a negative relationship with vacancy (Table 3, Figs. 1C, 2C). Neighborhoods with higher air temperature, more impervious surface area, and greater educational attainment had lower evenness (Table 3).

Within-neighborhood beta diversity was negatively correlated with air temperature (Table 3; Fig. 2D), where tree species composition within hotter neighborhoods was more similar, or there was lower beta diversity. Examining community composition across neighborhoods, we found that all of our neighborhood characteristics, except vacancy, were significant factors differentiating tree community composition (Table 4; Fig. 3), with significant differences in the centroids depending on our socio-environmental variables. For example, high- and middle-income neighborhoods had different street tree composition compared with low-income neighborhoods (Fig. 3B). In contrast, dispersion among neighborhoods within categories was related to vacancy only (Table 4), where high vacancy neighborhoods were more similar in composition to one another than were low vacancy neighborhoods, which were more different from one another in terms of community composition.

3.3. Tree condition

Baltimore neighborhoods had an average of 61.1 % trees in good condition and 9.7 % trees in poor condition (Table 2). Trees in poor condition are more common in neighborhoods with a higher proportion of Black residents, while neighborhoods with a higher proportion of White residents, higher household income, and greater educational attainment have lower proportions of trees in poor condition (Table 3). Similarly, the proportion of trees in good condition was positively correlated with the proportion of White residents (Fig. 2E), household income, and educational attainment, and negatively correlated with percent of Black residents. Finally, the percent of trees that were dead in a neighborhood was positively correlated with percent of Black residents, and negatively correlated with percent of White residents, educational attainment, impervious surface area and air temperature (Table 3).

4. Discussion

Socioeconomic and cultural resources interact with biophysical conditions of the urban environment to produce distribution of natural resources across the urban landscape (Machlis et al., 2005). Street trees are especially subject to human management and policies, as they are typically planted (though self-seeding is possible), and are often preemptively removed before senescence due to safety or aesthetic concerns. Thus, factors such as redlining (Schell et al., 2020), infrastructure limitations (Mullaney et al., 2015), and resident perceptions (Coleman et al., 2021; Fernandes et al., 2019) may all contribute to urban forestry policy and management, and their legacies may be observed in the distribution, composition, and condition of street tree populations. Our study identifies relationships among socioeconomic neighborhood characteristics and street tree condition and stocking rates that illustrate patterns of inequalities related to race, income, and education. We also identify neighborhood air temperature and impervious surface cover as significantly related to street tree size and diversity measures. The neighborhood scale chosen is meaningful to community residents, policymakers, and natural resource managers so that insights may be used to inform present and future management of street tree populations.

As expected, the total potential number of street tree sites was significantly positively correlated with total road length, reflecting the fact that neighborhoods with more streets have room for more street trees, despite neighborhood variation in land use and other aspects of the built environment. However, total number of street tree sites was not

Table 3
Correlation coefficients of socio-environmental and street tree variables.

	Black population (%)	White population (%)	Median household income (USD)	Bachelor's degree (%)	Vacancy (%)	Air temperature (°C)	Impervious surface cover (%)
Potential sites	−.08	.10	.19	.26	.11	.03	.03
Stocking (%)	−.61*	.58*	.45*	.63*	−.20	.24	.29
Sites above target pit size (%)	.31	−.33*	−0.23	−.39*	−.28	−.62*	−.81*
Rarefied species richness	−.14	.23	.22	.17	−.35*	−.66*	−.65*
Evenness	.29	−.24	−.19	−.34*	−.17	−.45*	−.50*
β Diversity	−.02	−.03	−.10	−.20	−.20	−.33*	−.27
Average DBH of small species (cm)	.27	−.13	.00	−.05	−.21	−.56*	−.53*
Average DBH of large species (cm)	.29	−.17	−.05	−.16	−.30	−.76*	−.78*
Good condition (%)	−.41*	.40*	.39*	.45*	−.30	.22	.23
Poor condition (%)	.38*	−.34*	−.37*	−.37*	.17	−.22	−.28
Dead (%)	.39*	−.37*	−.26	−.38*	.04	−.34*	−.38*

Note: This table presents Pearson correlation coefficients * $p < .05$.

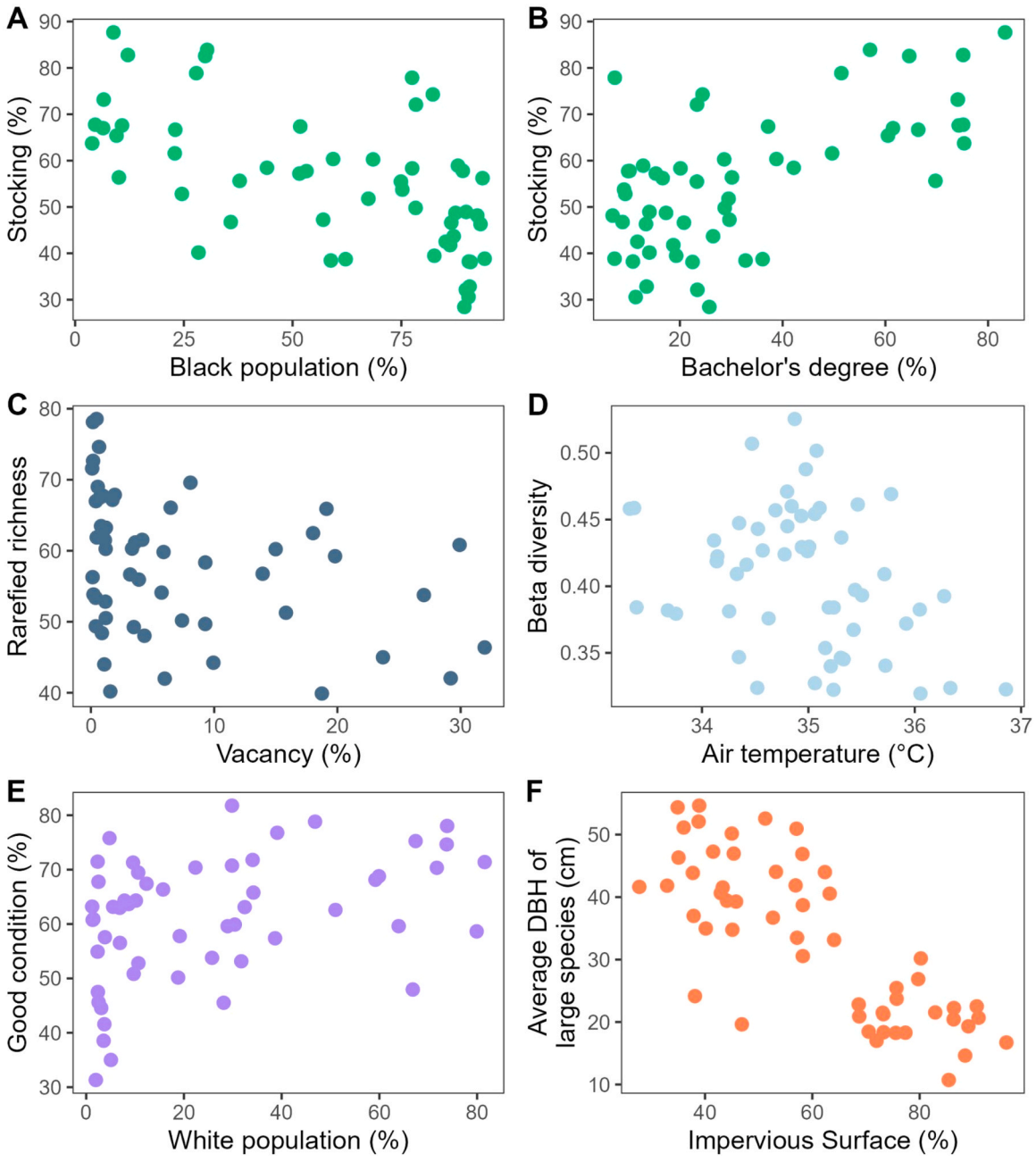

Fig. 2. Relationships between socio-environmental variables and street tree characteristics among Baltimore City neighborhoods (n = 54). (A) Percent Black population vs. stocking rate (percent of potential and available tree pits filled), (B) educational attainment (percent of residents over 25 with a bachelor's degree or higher) vs. stocking rate, (C) vacancy rate vs. species richness, (D) air temperature vs. beta diversity, (E) percent White population vs. percent of trees in good condition, (F) impervious surface cover vs. average DBH of large species.

Table 4
Results from PERMANOVA (differences in centroids) and PermDisp (differences in dispersion) tests for differences in beta diversity. Statistically significant values are denoted with an asterisk.

	CENTROIDS		DISPERSION	
	F-value	p-value	F-value	p-value
Temperature	4.86	0.001*	1.02	0.33
Income	2.32	0.023*	0.59	0.45
Vacancy	1.09	0.30	5.37	0.03*
Race	2.08	0.04*	0.013	0.92
Education	4.3.67	0.003*	0.03	0.85

significantly correlated with any other socio-environmental variables. This result demonstrates that neighborhoods varying widely in socio-economic status and environmental characteristics have the potential for a similar number of street trees. In contrast, our stocking analyses indicated that neighborhoods with higher proportions of Black residents and lower median household income had lower street tree stocking levels (percentage of potential street tree sites filled with live trees). Race and education were found to be important determinants of street tree density in New York City (Lin et al., 2021) and affluence was found to be a determinant in Nairobi, Kenya (Gerow et al., 2024) and Minas Gerais, Brazil (Pena et al., 2024), but these studies did not assess stocking rate by taking into account opportunities for additional street trees. Street trees are often planted and survive in wealthier neighborhoods where residents may be able to dedicate more time and resources

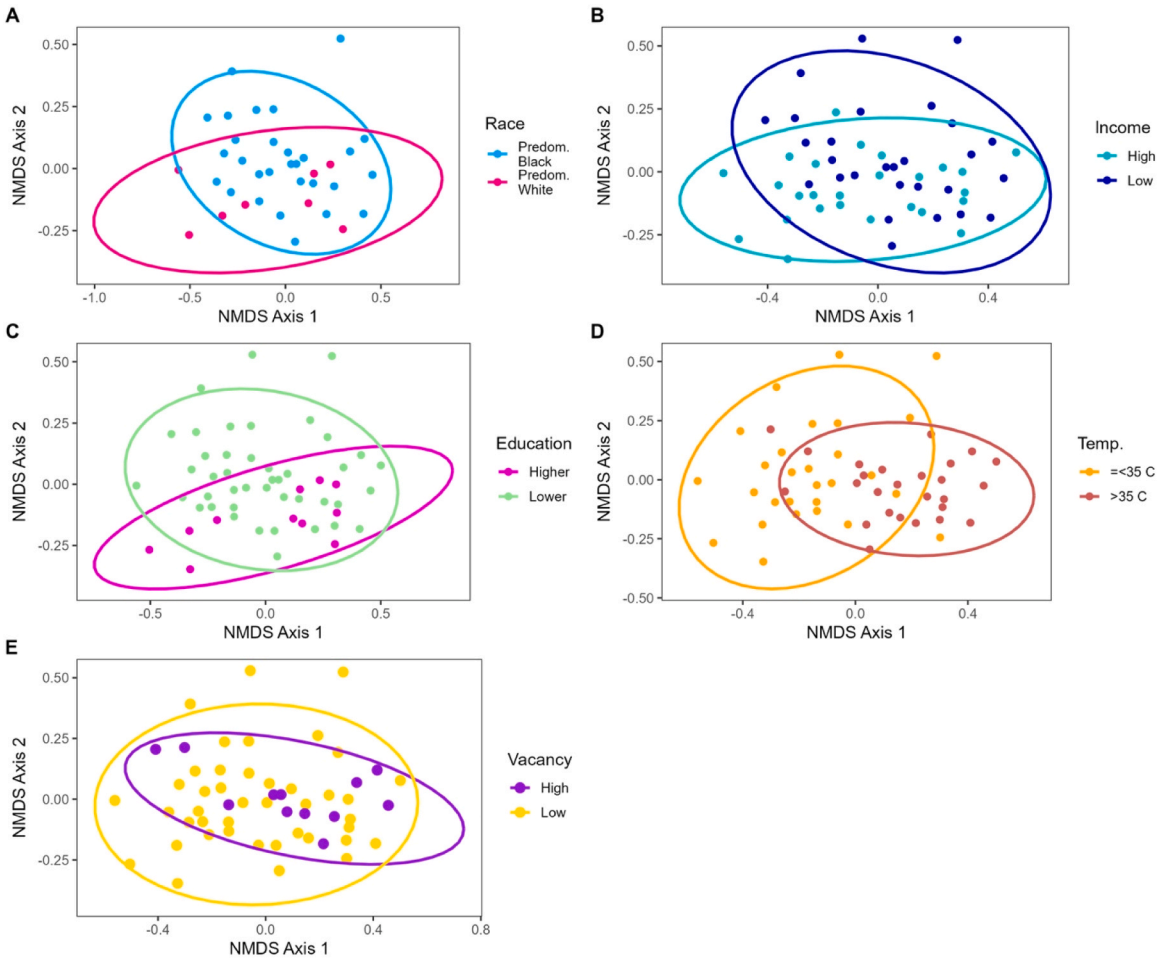

Fig. 3. NMDS of neighborhood community compostion comparing (A) predominantly Black and predominantly White neighborhoods, (B) low- and high-income neighborhoods, (C) neighborhoods with higher and lower educational attainment, and (D) neighborhoods with average air temperature = < 35 C or > 35, and (E) nieghborhoods with high and low vacancy rates. Ellipses represent 95 % confidence intervals.

to form relationships with tree planting organizations and request tree plantings (Pincetl et al., 2013; Lin, 2021). Additionally, fewer requests for tree planting may come from less affluent neighborhoods due to a perceived burden of maintenance or lack of involvement in decision making processes (Carmichael and McDonough, 2018). In an effort to address these challenges, the city's TreeBaltimore program seeks to increase awareness and remove barriers to neighborhood access to municipal resources for expanding and maintaining the city's tree canopy, including street trees (Sonti et al., 2024). Still, there appears to be an opportunity to plant additional trees in neighborhoods with a greater proportion of Black residents, although further ground-truthing of potential tree sites is necessary.

Similarly, we demonstrated socioeconomic inequities regarding street tree condition. Overall, neighborhoods with higher income and educational attainment and a greater percentage of White residents have healthier street trees than neighborhoods with a greater percentage of Black residents. It is particularly noteworthy that the proportion of trees in poor condition was significantly positively correlated with proportion of Black residents and significantly negatively correlated with income, education, and proportion of White residents given that trees in poor condition were considered critically damaged and are not likely to survive for many additional years. Black residents may suffer the consequences of critically unhealthy and dead street trees, which provide fewer ecosystem services than healthy trees both at present and into the future. This disparity may negatively influence the attitudes of these residents and their perceptions of street trees (Coleman et al., 2021). Now that this pattern has been identified, urban forest managers and communities can plan ahead to anticipate replacement of declining street trees in socioeconomically vulnerable neighborhoods. The reduced benefits provided by trees in worse condition may be offset by larger tree sizes, which greatly enhance provision of benefits. We did not find significant correlations between race, income, or education and tree size. More detailed tree size and condition data collection (i.e., tree height and percent crown dieback) could allow for a comparison of modeled ecosystem service provision across neighborhoods. Most Baltimore neighborhoods fail to meet the 10–20–30 criteria, and all fail to meet the 5–10–15 criteria, indicating a need to improve the city's street tree diversity to foster resilient street tree populations. Recent analyses have shown that most cities fall short of this goal (Galle et al., 2021; Kendal et al., 2014). Like many other cities in the Midwest and northeast United States (Cowett and Bassuk, 2017; Ma et al. 2020), we found a high proportion of *A. rubrum* trees. There are many reasons that cities struggle to increase the diversity of their street tree populations, including harsh urban growing conditions and nursery supply of diverse planting stock (Hilbert et al., 2023; Koeser et al. 2024).

Contrary to our predictions, we did not find significant relationships between race, income or education and street tree species richness or beta diversity. Human resource abundance (wealth) is often found to be an important driver of urban plant diversity, in a relationship called the "luxury effect" (Hope et al., 2003). Other studies have found evidence for the "luxury effect" in street tree communities, with greater species richness in affluent neighborhoods of Nairobi (Gerow et al. 2024) and

greater beta diversity of native species in Minas Gerais, Brazil (Pena et al., 2024). A previous study in Baltimore found that residential yard trees were more abundant, diverse, and larger in higher-income neighborhoods (Avolio et al., 2020). However, street tree populations are formed through a combination of public policy and private resources (Padullés Cubino and Retana, 2023; Avolio et al., 2018) and may be less diverse than yard trees at private residences in the same neighborhood (Avolio et al., 2018).

While some studies have focused on socio-economic drivers of street tree distribution and diversity, fewer have investigated environmental parameters, which will directly impact the survivorship, growth and physiology of trees. We found that neighborhood impervious cover and air temperature strongly correlate with many aspects of Baltimore's street tree population, including species richness, evenness, and beta diversity. One study on trees in Orange County, CA found higher tree species richness in hotter areas (Avolio et al., 2015), while we found the opposite–lower species richness and evenness in neighborhoods with higher impervious surface cover and air temperature, as well as lower beta diversity in hotter neighborhoods. Baltimore's urban foresters have suggested that the heat and impervious surface cover in densely built neighborhoods limit their ability to increase species diversity because only a few species are able to successfully establish and survive under those environmental conditions (Sonti et al., 2024). Supporting this assertion, a recent study from Philadelphia, PA found that street trees surrounded by greater impervious surface cover have a lower chance of survival, while drought tolerant species have a greater chance of survival (Bigelow et al., 2024). Air temperature was not significantly correlated with any of our socioeconomic variables, suggesting that there are warmer neighborhoods of different demographic compositions with lower species richness, evenness, and beta diversity, consistent with the lack of significant correlations between neighborhood socioeconomic variables and tree diversity measures.

We also found air temperature and impervious surface cover to negatively correlate with target pit size, proportion of dead trees, and average DBH of both small and large stature tree species. Densely built neighborhoods lacking space for larger tree pits have higher air temperatures and other environmental stresses that may reduce street tree growth and/or shorten the lifespan of street trees, which could lead to smaller trees and more dead trees in these neighborhoods (Anys and Weiler, 2025). The lack of large, healthy street trees to provide shade and evapotranspirative cooling may further exacerbate the urban heat island effect in neighborhoods that do not have extensive green space. Though others have found aspects of the built environment to be better predictors of street tree distribution than socio-economic indicators (Schindler and Schindler, 2025), we did not find impervious surface or air temperature to correlate with street tree stocking.

We found that neighborhood air temperature, race, income, and educational attainment were significant factors differentiating neighborhood street tree community composition, and that neighborhoods with high vacancy rates had more similar community composition (less dispersion) than low vacancy neighborhoods. Baltimore neighborhoods with higher vacancy rates also exhibited lower species richness. These neighborhoods likely have less public and private investment in green space and are located in parts of the city that were originally built with high density development, leaving less room for street tree planting sites and potentially creating conditions where a narrower suite of species may survive (Sonti et al., 2024). Avolio et al. (2018) found that street trees in neighborhoods were more similar to one another depending on the age of the neighborhood, where younger neighborhoods had different tree community composition compared with older neighborhoods.

Our study is strictly observational and from a single point in time, and we cannot establish causal relationships from this study design. Rather, we have identified strong associations between Baltimore's street tree population and social-environmental factors across the urban landscape. Street trees are influenced by many socio-environmental factors not included in our analysis, such as air pollution, historic land use legacies, water availability, and stewardship. In addition, the street tree inventory used in this analysis was completed during 2017–2018 and the patterns found in this study cannot account for more recent street tree planting or removals. Baltimore's current tree planting initiatives indicate attention to alleviating some of the inequalities found in this study (Sonti et al., 2024). The city's TreeBaltimore program aims to expand Baltimore's tree canopy (BCRP, 2007) and Maryland's Tree Solutions Now Act targets the planting of 500,000 in underserved urban areas (Maryland DNR, 2023). Baltimore City's Sustainability Plan aims to increase the size of new and existing tree pits to meet the Forestry Division's standard of 32 ft^2 (3 m^2) (The Baltimore Office of Sustainability, 2019). Future research may inform these efforts by investigating perceptions and attitudes related to tree planting, maintenance, and diversity among Baltimore residents and other stakeholders.

Our findings demonstrate that socioeconomic factors are more strongly associated with Baltimore street tree stocking and condition, while environmental factors are correlated with street tree diversity and size. We find associations between traditionally marginalized populations and lower street tree stocking and tree health, highlighting opportunities for planting and maintaining robust street tree communities in socioeconomically vulnerable neighborhoods to improve resident access to valuable green infrastructure now and into the future.

In contrast to the previous study of Baltimore's formerly redlined neighborhoods, we did not find significant correlations between socioeconomic factors and street tree size or diversity. Instead, our results suggest that the built environment may pose biophysical constraints on enhancing and diversifying Baltimore's street tree population. There may be several reasons for the different findings observed here, including: (1) the historic HOLC map does not cover the entire present-day extent of Baltimore City included in our analyses, and (2) current neighborhood socioeconomic characteristics do not always reflect former HOLC grades (The Digital Scholarship Lab and the National Community Reinvestment Coalition, 2025). These differences between historical and present-day community characteristics motivated Baltimore natural resource managers' interest in the analysis presented here. While some of Baltimore's formerly redlined neighborhoods remain socially vulnerable, there are also redlined neighborhoods with high air temperatures and impervious cover and relatively low street tree diversity and DBH that have low social vulnerability today. Regardless of socioeconomic status, densely built neighborhoods can be challenging environments for street tree survival (Lu et al. 2010). Targeted interventions to improve soil volume and reduce impervious surface cover may enable a greater diversity of tree species to survive and reach larger sizes, allowing for enhanced ecosystem services including shading and evapotranspirative cooling effects (Yin et al. 2024). While not causal relationships, the correlations identified here represent conditions on the ground in Baltimore's neighborhoods and the street trees they contain. These findings may be used to guide urban forestry policy and programs related to street tree planting, management, and community stewardship to promote sustainability of Baltimore's urban forest.

CRediT authorship contribution statement

Trinidad (Trini) Fleming: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Avolio Meghan L.:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis. **Locke Dexter H:** Writing – review & editing, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sonti Nancy Falxa:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank our funding sources: USDA NIFA Award #2020-04369, DOE IFL Award # DE-SC00023217, and the U.S. Forest Service Northern Research Station. We thank our colleagues at Baltimore City's Forestry Division for providing street tree data and for their comments on our manuscript. The findings and conclusions in this publication are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2025.129105.

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