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Investigating Social-Ecological Linkages in Baltimore, MD: Environmental Stewardship, Green Stormwater Infrastructure, and Tree Canopy Change at the Neighborhood Level

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Investigating Social-Ecological Linkages in Baltimore, MD: Environmental Stewardship, Green Stormwater Infrastructure, and Tree Canopy Change at the Neighborhood Level

Environmental stewardship organizations in Baltimore play important roles in taking care of the local environment through conservation, management, restoration, monitoring, education, and other efforts. These diverse activities were captured in Baltimore's Stewardship Mapping and Assessment Project (STEW-MAP) surveys in 2011 and 2019. Despite previous research, knowledge gaps remain about the spatial and temporal dynamics of environmental stewardship groups and their relationships with elements of the built environment, such as green stormwater infrastructure (GSI) and tree canopy cover. Using spatial Bayesian regression, we examine how 1) voluntary GSI, 2) regulatory GSI, 3) tree canopy cover, and 4) tree canopy cover change vary by the number of local stewardship organizations related to stormwater management or trees, with and without controlling for impervious surface cover, median household income, race, ethnicity, and vacant housing. Voluntary GSI represents bottom-up community initiatives and was expected to be more strongly predicted by stewardship than regulatory GSI, which is implemented in a top-down manner by City agencies. Tree canopy cover and canopy change are the product of both bottom up and top-down tree planting, protection, and maintenance activities. Overall, the number of stewardship groups from either point in time was not a significant predictor of tree canopy or GSI of either type. However, 2011 tree stewardship groups were positively associated with tree canopy gain from 2013 to 2018, and 2019 tree stewardship groups were slightly negatively associated with tree canopy change. Adjusted models showed impervious surface was positively related to voluntary GSI, median household income was positively associated with tree canopy cover, and percent Black/African American was negatively associated with regulatory GSI. The findings raise questions about how stewardship activities are quantified and mapped, and the other plausible mechanisms that explain the spatial distribution of GSI and tree canopy cover. More long-term quantitative data, augmented with qualitative, engaged and process-based inquiry might be needed to more holistically understand local stewardship motivations and actions and the potential outcomes of the myriad groups who care for their neighborhoods.

Keywords

environmental stewardship, tree canopy, tree canopy change, sociodemographic factors, green stormwater infrastructure, Baltimore, social-ecological systems

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1. INTRODUCTION

Aldo Leopold describes "land ethic" as the moral responsibility towards the environment and such responsibility can be achieved through stewardship (Leopold 1949). Environmental stewardship can be defined as actions towards conservation, management, monitoring, advocacy, or education about local environments (Fisher et al., 2012; Romolini et al., 2013; Svendsen & Campbell, 2014). Stewardship organizations have a wide variety of legal designations, including public, private and nonprofit groups. The activities provided by stewardship organizations can range from tree planting, ecosystem restoration, and pollution mitigation to environmental education and community improvement. The capacity to steward is an important factor in how individuals and communities engage with their local environment. Bennett et al. (2018) suggested two main factors affect, positively or negatively, the capacity to steward: local community assets and broader governance factors. Local community assets can be defined by the amount of local resources in the community, including social capital (e.g., relationship networks), cultural capital (e.g., sense of place and traditions), financial capital (e.g., income), physical capital (e.g., technology and infrastructure), human capital (e.g., individual knowledge, skills, and sociodemographic factors), and institutional capital (e.g., agency and empowerment) (Bennett, 2010; Bennett et al., 2012). Governance factors, including decision-making processes, policy frameworks, laws, and other structural processes, can determine the presence or absence of a community sense of empowerment and agency (Lockwood et al. 2010; McLaughlin and Dietz 2008).

The philosophy of environmental stewardship is integrated in the *ecology for the city* paradigm, linking ecological science with civic processes (Cadenasso & Pickett, 2013; Krasny & Tidball, 2012; Pickett et al., 2016). This paradigm builds off of and adds complexity to the *ecology in* and *ecology of the city* paradigms, as it moves from a biotic or ecological community focus to a collaboration among residents, agencies, technical staff, and decision makers to connect urban ecological science with social equity, environmental integrity, and economic viability concepts. Consequently, this paradigm relies on and results in a holistic social-ecological systems approach (Pickett et al. 2016). Such an approach takes into consideration the reciprocal influences of social factors and their surrounding environments. For example, a variety of socio-economic factors have been shown to relate to vegetation cover, biodiversity, and ecosystem service provision (Aznarez et al. 2023; Locke, Hall, et al. 2021; Nix et al. 2023). Meanwhile, urban ecological knowledge is thought to be important for guiding community-based tree planting programs (Hilbert et al. 2022) and the creation of meaningful place-based stewardship programs (McMillen et al. 2020).

Buijs et al. (2016) suggested stewardship could increase environmental, social, and institutional resilience of cities by improving habitat connectivity, promoting social cohesion, and driving institutional innovation. Additionally, Colding et al. (2013) supported the idea that stewardship contributes to environmental resilience by creating urban green spaces, improving maintenance efforts, and promoting green space restoration. Consequently, civic engagement with urban ecosystems leads to an increase of ecosystem services, such as reduction of carbon dioxide, biodiversity and pollination enhancement, and eco system restoration after extreme weather events (Barthel et al., 2015; Chan et al., 2015; Dennis & James, 2016).

Green stormwater infrastructure (GSI) and urban tree canopy cover are considered elements of urban ecological infrastructure (Childers et al. 2019). As infrastructure, GSI and urban tree canopy are both multifunctional, in that they provide a suite of ecosystem services across neighborhoods and at regional scales (Lovell and Taylor 2013). These ecosystem services are thought to improve resilience and sustainability for cities (McPhearson et al. 2015; Meerow and Newell 2017) by managing extreme heat, mitigating stormwater flows, reducing air pollution, and providing aesthetic, recreational, and health benefits. Therefore, understanding how GSI, tree canopy cover, and tree canopy change are developed, distributed, and maintained in cities in order to increase the provision of ecosystem services is a frontier for both environmental research and practice. Due to their multifunctionality, implementation and maintenance of GSI and urban tree canopy cover require participation from various partners (e.g., non-profits, government agencies, and private companies) and input from both ecological and social components. Stewardship may be one link that connects social and ecological factors in cities to affect stormwater management and forestry t practices (Andersson et al. 2014; Campbell et al. 2022).

The spatial distribution of GSI, tree canopy cover, and canopy change may differ across neighborhoods due to differences in population density, sociodemographic factors, green space density, hydrologic soil type, environmental stewardship initiatives, and urban planning strategies. For instance, at the census block group scale, there is greater canopy cover and GSI in areas of Baltimore with more available space, such as outside the city center and in areas with a lower population density and more green space (Baker et al. 2019). New private developments and public retrofits may drive GSI implementation and tree planting, as they are being designed in accordance with current urban forestry and stormwater management regulations (e.g., Chesapeake Bay Total Maximum Daily Load). Additionally, sources of funding (e.g., private or public) and environmental equity efforts for tree planting and GSI installation can be a significant driver of differences in correlations between GSI density (Chan & Hopkins, 2017), urban tree canopy cover (Schwarz et al. 2015), and sociodemographic characteristics. Yet the majority of this quantitative research uses cross-sectional analyses, without data on changing stewardship or neighborhood conditions.

The current vegetation in the neighborhood and past experiences with social and environmental projects are endogenous drivers of landscape structure (e.g., infrastructure and land cover) and landscape function (e.g., infiltration of stormwater, shading, and aesthetics) (Roman et al. 2018; Shandas 2015). Additionally, the physical properties of soils, specifically their infiltration rate and runoff potential, may facilitate or prevent the allocation of GSI in certain neighborhoods (Chan & Hopkins, 2017; Locke, Phillips de Lucas, et al. 2021). It is important to understand how these social and biophysical components influence the planning and implementation process of GSI and tree canopy expansion. The lack of intentional design and siting of GSI and tree canopy in neighborhoods where they are most needed may lead to environmental injustice implications and failure to promote resilience and deliver ecosystem services to local communities.

In addition to these biophysical and social factors, the existence of environmental stewardship initiatives can boost the installation of GSI, tree conservation, and tree planting. For example, the Grey-to-Green Initiative, a five-year program that worked with communities to install stormwater management practices, plant trees, and preserve land, , created a high density of GSI in Portland, OR (Chan & Hopkins, 2017). Thus, neighborhoods with more community access and involvement with such initiatives may have a higher density of environmental amenities than neighborhoods with less public engagement. Stewardship can also impact the health of urban ecological systems through promotion of maintenance programs. For instance, forest stewardship programs enhanced the survivorship of newly planted trees and allowed afforestation programs to cope with the effects of drought in Holyoke, MA (Breger et al. 2019). In another example, neighborhoods in New York City with more stewardship groups tended to gain vegetation cover from 2000 to 2010, which was a period where most neighborhoods lost vegetation (Locke et al. 2014). Previous loss of vegetation and building footprint gain may have motivated stewardship activity such as the addition of grassroots environmental stewardship to conservation and preservation efforts in these neighborhoods (Locke et al. 2014).

Knowledge gaps still remain about the spatial dynamics of environmental stewardship groups and their relationships with the built and vegetative environment over time. In particular, stormwater management and tree canopy are two topics of increasing concern in urban sustainability policy and management (City of Baltimore 2019). We examine regulatory GSI and voluntary GSI to serve as comparison, allowing us to investigate potential differences in stewardship associations between the two. We hypothesized that stewardship organizations filtered for stormwater management may show no significant association with regulatory GSI, while these stewardship organizations could show a positive association with voluntary GSI, reflecting potential proactive actions among groups that lead to enhanced creation and maintenance of GSI. GSI advocacy and implementation take time. As well, tree planting, tree maintenance, and forest management may not impact tree canopy estimates immediately. In both cases, we expect stewardship groups' efforts to be reflected several years later. Using a unique repeated survey of environmental stewardship groups in 2011 and 2019, our study aims to investigate how community action might be shaping urban ecosystem structure over time. Near-term (~5 years) tree canopy change data allow for an examination of changes in the number of groups and changes in tree canopy simultaneously. Do neighborhoods with more stewardship groups that focus on stormwater or trees have more GSI or more tree canopy cover, and canopy gain? Using spatial Bayesian regression, we examine how (1) voluntary GSI, (2) regulatory GSI, (3) tree canopy cover, and (4) tree canopy cover change vary by the number of local stewardship organizations related to stormwater management or trees in 2011 and 2019, with and without controlling for impervious surface cover, median household income, race, ethnicity, and vacant housing. The 2011 and 2019 stewardship data enable us to investigate potential temporal lags between prior stewardship group presence and present-day environmental conditions. Results from these analyses may inform citywide and regional natural resources management and ultimately create more resilient neighborhoods and cities.

2. MATERIALS AND METHODS

2.1. Study site description

Baltimore, MD (39° 17' 57.2496" N, 76° 36' 33.7788" W) is located in the Mid-Atlantic region of the US and is located in the northern portion of the Chesapeake Bay. Baltimore has an estimated 2020 population of 585,708 people, a 6% decrease from the total population in 2010, with 57.8%

Black, 28% White, and 7.8% Hispanic or Latinx; and a median household income of $45,221 (Figure 1) (US Census 2020). In 1950, Baltimore City was the sixth-largest city with 950,000 people and it was a leading port and industrial hub. However, deindustrialization caused a shift in economic and social structure in the city leading to a wave of suburbanization and a declining population (Levine 2000). Historical racial segregation policies in Baltimore's neighborhoods have resulted in environmental, economic, education and public health inequities (Boone 2002; Burghardt et al. 2022; Grove et al. 2018; Huang and Sehgal 2022; Locke, Hall, et al. 2021). The canopy cover in Baltimore City is on average 26.85% per neighborhood across all land uses, ownerships, and types of green space (Table 1). This paper uses the Baltimore City Department of Planning neighborhood boundaries (N = 278) as the unit of analysis, since they are familiar to residents, and the STEW-MAP survey (described next) collected data corresponding to those boundaries. Neighborhoods range in size from ~14.5 acres (Lower Edmondson Village) to ~1592 acres (Canton Industrial Area), with an average size of 187 acres, and a median of 115 acres.

2.2. Data

The GSI dataset used in this analysis primarily included visible and discrete installations with aboveground components that could be precisely mapped within property boundaries, excluding projects such as underground filters, and projects such as pollinator gardens that involved only planting of vegetation without specific stormwater features. The selection criteria and GSI installation types included in the data are described in further detail by Solins et al. (2023). Briefly, regulatory GSI data were obtained from Baltimore City Department of Public Works. Regulatory GSI facilities were installed to satisfy the requirements of development and redevelopment projects in a municipal separate storm sewer system (MS4) discharge permit. This regulatory GSI database was submitted to the Maryland Department of the Environment in 2018 as part of the requirement for Baltimore's MS4 permit reporting, and it is the most updated GSI dataset from the city as described by Solins et al. (2023). Regulatory GSI were focused on aboveground facilities that contain plants and thus may be more obvious from the street and provide ecosystem services (as described by Baker et al. (2019)). The data for voluntary GSI facilities was collected by Solins et al. (2011) and refers to installations by non-governmental organizations (NGOs) and community groups with the goal of serving organizational missions and leveraging funding opportunities. Voluntary GSI data were obtained from nonprofit partners and Baltimore's Department of Public Works in 2019 through publicly available data sources (e.g., annual reports and newspaper articles). Most of these voluntary installations were completed between 2014 and 2017 (Solins et al. 2021). Organizations responsible for implementing voluntary GSI included non-profit organizations such as the Parks & People Foundation, Blue Water Baltimore, Civic Works, and church and community groups.

Of the 278 neighborhoods, only 80 (28.7%) contained voluntary GSI, 106 (38.12%) contained regulatory GSI, and 37 (13.3%) contained both voluntary and regulatory GSI (Figure 1). Therefore, a large number of neighborhoods in Baltimore did not contain any GSI, resulting in many zeros in the counts of GSI of either type at the neighborhood level. We used the presence or absence of GS Ias a variable instead of counts. This approach, used in previous studies, helped minimize potential skewing effects in statistical models that can arise from highly sparse data with predominant zero values and allowed for comparability (Baker et al., 2019; Solins et al., 2023).

Percent tree canopy in each neighborhood was determined using a 1-meter resolution land use and land cover data representing year 2018 conditions (Chesapeake Bay Program 2023). The tree canopy and impervious surface classes were summarized at the neighborhood level using the Tabulate Area (Spatial Analyst) tool in ArcGIS Pro ("ArcGIS Pro" 2022). Percent tree canopy cover was summarized by summing all tree classes by neighborhood: forest, tree canopy (other), tree canopy over turf grass and tree canopy over impervious. Tree canopy change was created as the relative percent change, which is the percent canopy in time 2 (2018) minus the percent tree canopy cover in time 1 (2013), divided by the percent of tree canopy cover in time 1. Changes are therefore the percentage point change relative to 2013 conditions. One neighborhood, Dundalk Marine Terminal, had zero tree canopy cover in time 1 and was therefore excluded from the analysis because a quantity cannot be divided by zero. Percent impervious cover was determined by summing all impervious classes by neighborhood: roads, impervious structures, tree canopy over impervious, and other impervious surfaces.

A spatial database of Baltimore, MD stewardship groups and associated characteristics for 2011 and 2019 was obtained from the Stewardship Mapping and Assessment Project (STEW-MAP) survey developed by the USDA Forest Service (Sonti et al. 2023). The goal of STEW-MAP is to identify groups who work to conserve, manage, monitor, transform, educate, and advocate for the local environment, their networks, and the areas where they work (Svendsen et al., 2016; Campbell et al 2024). Information collected in the surveys included contact information and organizational characteristics related to staffing, funding sources, budget, organizational focus, and stewardship site types (see Table S1 for selected organizational characteristics). Further details about survey preparation, sampling methods, database design, survey implementation, data collection, and data management are described by Svendsen et al. (2016). We filtered the stewardship group survey data to include only organizations who work on our environmental features of interest: GSI and trees. GSI-related stewardship groups were filtered based on organizations' site types related to stormwater features (including rain gardens, rain barrels, permeable pavement, and bioswales) or green roofs in 2011 and 2019, and based on organizational focus on stormwater in 2019 (this question was not asked in 2011). Tree-related stewardship groups were filtered based on organizations' site types related to trees (including community gardens, street trees, parks, forests, greenways, public gardens) in both 2011 and 2019 and based on organizational focus on trees in 2019. Filtering stewardship organizations for GSI resulted in 65 and 24 stewardship organizations in 2011 and 2019, respectively. Similarly, filtering for tree-related organizations resulted in 112 and 69 stewardship organizations in 2011 and 2019, respectively. The count of these groups per neighborhood level, divided by the neighborhood area was used to account for varying neighborhood size. Citywide groups were excluded from the analyses to maintain focus on the neighborhood scale; retaining citywide groups would rescale the estimates accounting for 29 and 53 organizations, for 2011 and 2019, respectively, since all neighborhoods would be affected. Including citywide groups therefore does not help us to understand the relationship between neighborhood-level stewardship and GSI or tree canopy cover. We thus generated four stewardship group variables: the number of GSI groups per km^2 and the number of tree-related groups per km^2, excluding city-wide groups, for 2011 and 2019 (Figure 2). Baltimore neighborhood boundaries were obtained from the "Open Baltimore" data portal (https://data.baltimorecity.gov/).

Sociodemographic characteristics were obtained from the Baltimore City Department of Planning at the neighborhood level. Their dataset was generated from the 2020 US Census by spatially joining Census blocks to neighborhoods based on their centroid (US Census 2020). From this dataset, we determined race (percent of the population identified as Black) and ethnicity (percent of the population identified as Hispanic or Latinx) for each neighborhood. Median household income data was summarized by neighborhood from the US Census 2020 dataset using the Enrich layer tool in ArcGIS online (ESRI Inc.), using a weighted centroid geographic retrieval approach for data apportionment (ESRI, n.d.).

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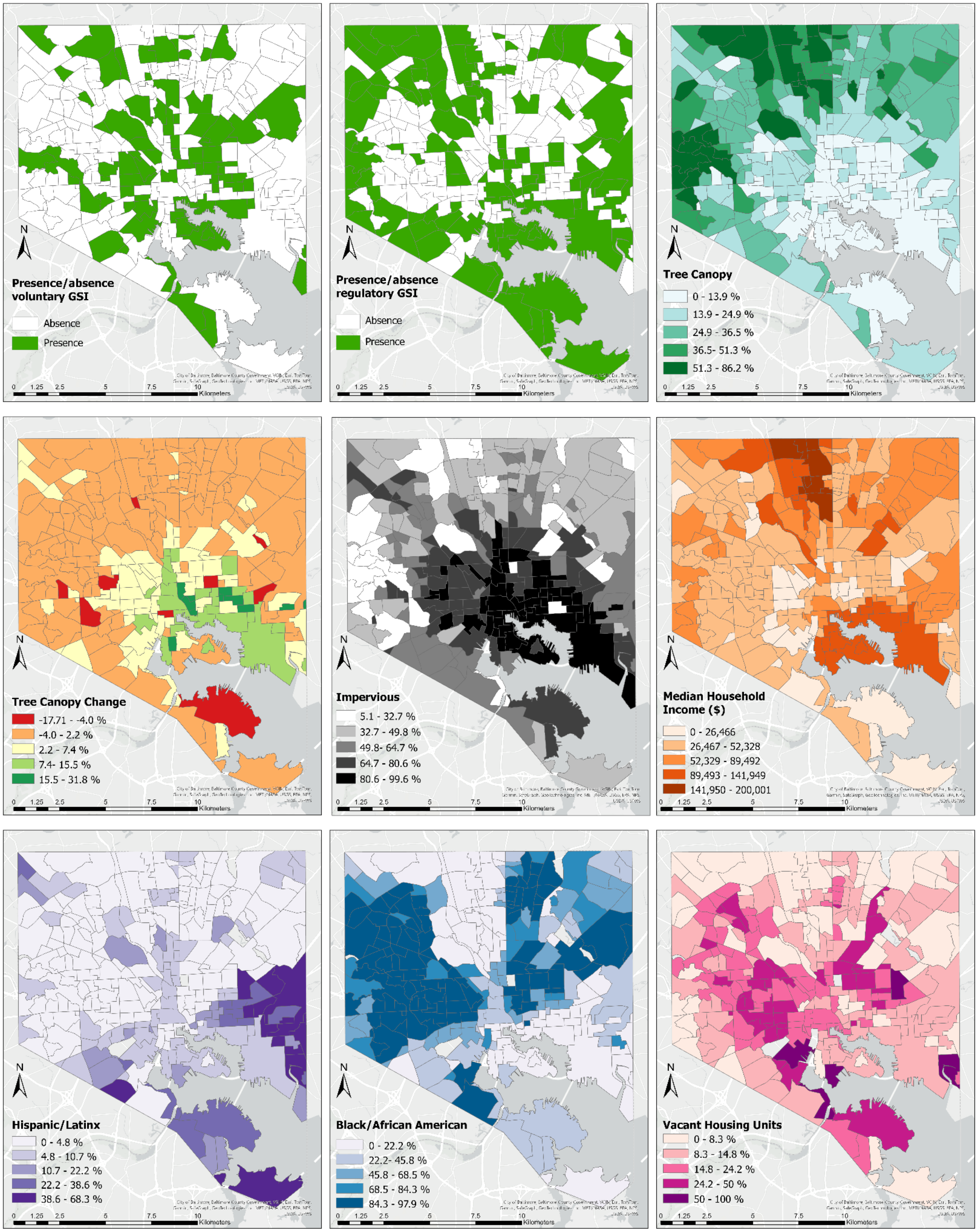

Figure 1. Landscape characteristics, sociodemographic factors, and presence/absence of voluntary and regulatory green stormwater infrastructure (GSI) in Baltimore's neighborhoods. Data for each continuous variable were classified into five Jenks natural breaks.

2.3. Data analysis

Stewardship groups pertaining to GSI and trees were regressed against the presence of GSI installations (regulatory and voluntary, separately), tree canopy (cover and change), respectively, to see how stewardship groups are associated with these aspects of the urban environment. Voluntary GSI are expected to be related to stewardship groups, while regulatory GSI are not. Since GSI and tree canopy take time to be planned, designed, and implemented, and thus appear on the landscape in ecological datasets, we used counts of stewardship groups per neighborhood in both 2011 and 2019. These natural resource-specific, longitudinal measures of groups per neighborhood are intended to account for temporal lags. Although we cannot make causal claims about stewardship group presence and the built environment, this study design advances over single point in time snapshots by documenting spatio-temporal patterns that allow the generation of hypotheses regarding dynamic linkages between stewardship and the built environment.

For each dependent variable (voluntary GSI, regulatory GSI, tree canopy cover, and tree canopy cover change), we fit the Bayesian spatial regression models twice: once with (hereafter "adjusted") and again without (hereafter "unadjusted) controlling for impervious surface cover, median household income, race, ethnicity, and vacant housing, creating a total of eight models. Impervious surface cover was not included in the models estimating tree canopy cover or canopy cover change because they are derived from the same land cover file and are consequently likely to be correlated, with highly impervious neighborhoods having less space for extensive tree canopy. The GSI variables were binary, so a binomial distribution was used, for tree canopy cover a beta distribution was used, and the tree canopy change measure had wide tails so a Student's T distribution was used. All models had a logit link function, except for tree canopy change, and the spatially-autocorrelated random effects.

All statistical analyses were done in R version 4.3.2 (Bivand and Wong 2018; Parry and Locke 2024; Pebesma 2018; R Core Team 2023; Wickham et al. 2019). Because neighborhoods were the unit of analysis, we expected the data to be spatially autocorrelated (Figure 1, Figure 2, Table 1), violating the independence assumption for regression. Moran's I values confirmed spatial autocorrelation, meaning that nearby locations had values more similar than chance alone (Table 1). To address the lack of independence from the spatial data, the Besag-York-Mollié (BYM) specification was used (Besag, York, and Mollié 1991). Briefly, the BYM model adds two unit-level random intercepts (in addition the fixed effects of interest), one that is spatially autocorrelated (ϕ) and another for non-spatial heterogeneity (θ). The former can be thought of as structured, and the later random noise. Together they encapsulate spatial autocorrelation and allow for reliable estimates of the remaining regression coefficients. A queen contiguity matrix was used, which defined neighbors as block groups sharing an edge or vertex (Locke, Phillips de Lucas, et al. 2021). Models were fit using Integrated Nested Laplace Approximation (INLA) via R-INLA version 23.09.09 (Lindgren and Rue 2015; Rue, Martino, and Chopin 2009). INLA is a commonly-used alternative to Markov Chain Monte Carlo (MCMC) estimation of posterior probability distributions in Bayesian analyses; as of April of 15, 2022 INLA had more than 250 known published uses for COVID-19 mapping alone (Van Niekerk et al. 2023). Rather than sampling parameters for model fitting like MCMC, INLA approximates the marginals using integrals. We report the median posterior estimate in log-odds and 95% credible intervals, the Bayesian analogue to confidence intervals.

Table 1. Continuous variables used in data analyses. All variables are summarized at the neighborhood level; all Moran's I values were significant at the p<0.0001 level.

Variable	Mean	Standard Deviation	Moran's I	Source	Group
2018 tree canopy cover (%)	26.88	16.39	0.66	Chesapeake Bay Program, 2022	Land use and land cover
2013-2018 tree canopy cover change (%?)	2.85	5.47	0.37	Chesapeake Bay Program, 2022	Land use and land cover
2019 GSI stewardship groups*	0.23	1.32	0.20	USDA Forest Service, Sonti et al., 2023	Environmental Stewardship
2011 GSI stewardship groups*	2.60	5.46	0.45	USDA Forest Service, Sonti et al 2023	Environmental Stewardship
2019 tree stewardship groups*	2.41	5.99	0.39	USDA Forest Service, Sonti et al 2023	Environmental Stewardship
2011 tree stewardship groups*	5.57	8.32	0.40	USDA Forest Service, Sonti et al 2023	Environmental Stewardship
Impervious cover (%)	59.60	21.26	0.59	Chesapeake Bay Program, 2022	Land use and land cover
Median Household Income ($1000s, 2021)	55.78	36.05	0.59	US Census, 2020	Sociodemographic
Hispanic/Latino (%)	8.40	12.14	0.64	US Census, 2020	Sociodemographic
Black/African American (%)	58.14	33.84	0.69	US Census, 2020	Sociodemographic
Vacant Housing Units (%)	16.00	13.23	0.16	US Census, 2020	Sociodemographic
*stewardship group measures exclude city-wide organizations and are normalized as counts per square kilometer					

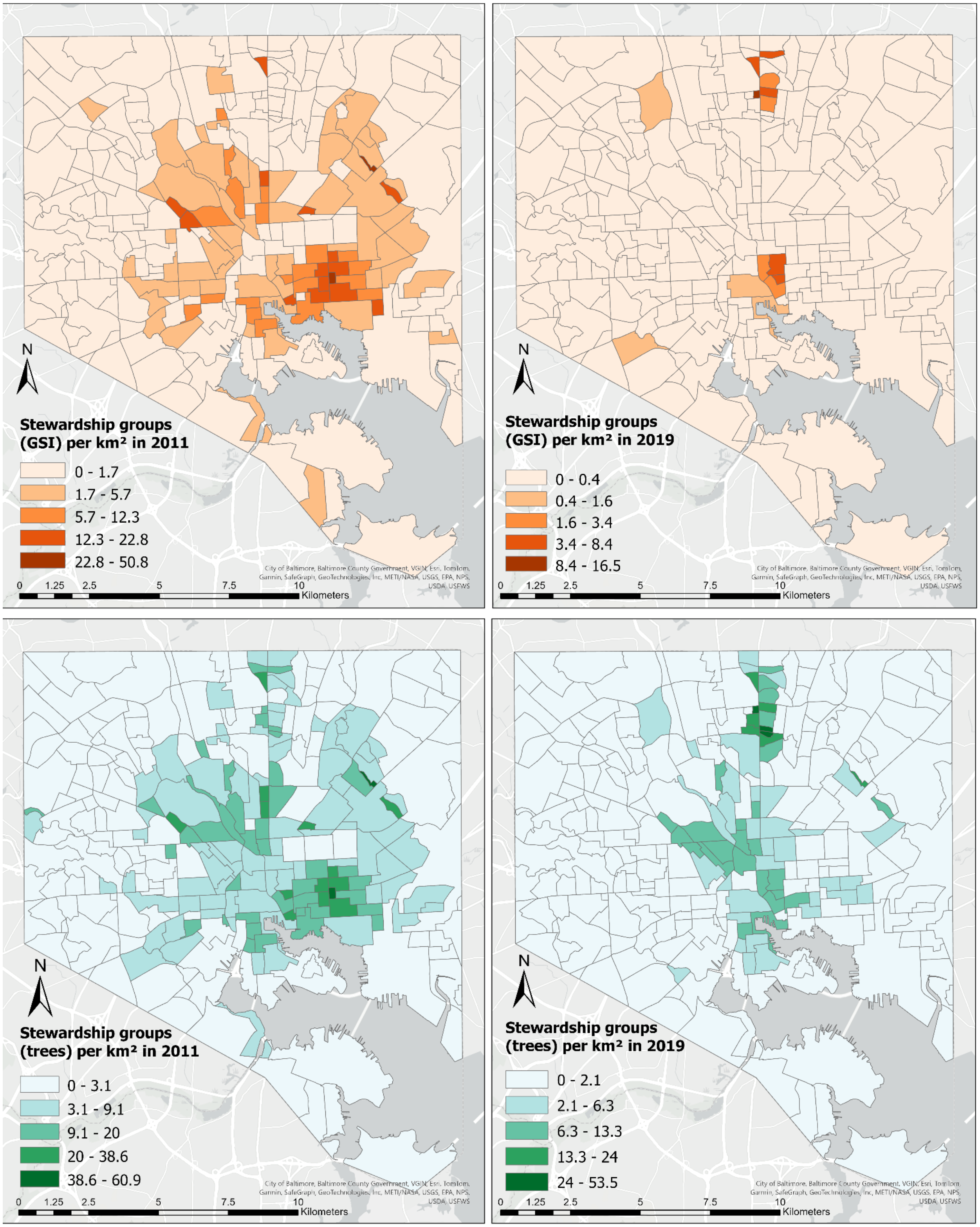

Figure 2. Subsetted stewardship groups related to green stormwater infrastructure (GSI, top) and trees (bottom) in 2011 (left) and 2019 (right) in Baltimore's neighborhoods. Data were classified into five Jenks natural breaks.

3. RESULTS

Supplemental Table 1 summarizes some characteristics of the GSI- and tree-focused stewardship groups that responded to the STEW-MAP survey in either 2011 or 2019. The majority of organizations are non-profit or other community groups, although this percentage is slightly lower for 2019 GSI stewardship groups. Organizations have as few as zero full-time or part-time staff and as many as 350 full-time staff, and the mean number of staff range from 3-25 depending on the survey year and stewardship focus (GSI or trees). The number of members and regular volunteers affiliated with the groups range even more widely from zero to thousands. The organizations range in age from centuries (founded in 1797) to less than a year (founded in 2019).

In the unadjusted GSI models, the only significant relationship was a positive association between 2011 GSI stewardship groups and voluntary GSI spanning 2014-2017. That significant finding did not hold in the adjusted models, which contained covariates such as demographics, impervious surface, and housing vacancy. Adjusted models showed that impervious surface was positively related to voluntary GSI and percent Black/African American population was negatively associated with regulatory GSI.

Similarly, in the unadjusted tree canopy models, the only significant relationship was a positive association between 2011 tree stewardship groups and 2013-2018 tree canopy change. This finding held in the adjusted models, as well as a small but significant negative association between 2019 tree stewardship groups and tree canopy change, and a significant positive association between median household income and 2018 tree canopy cover.

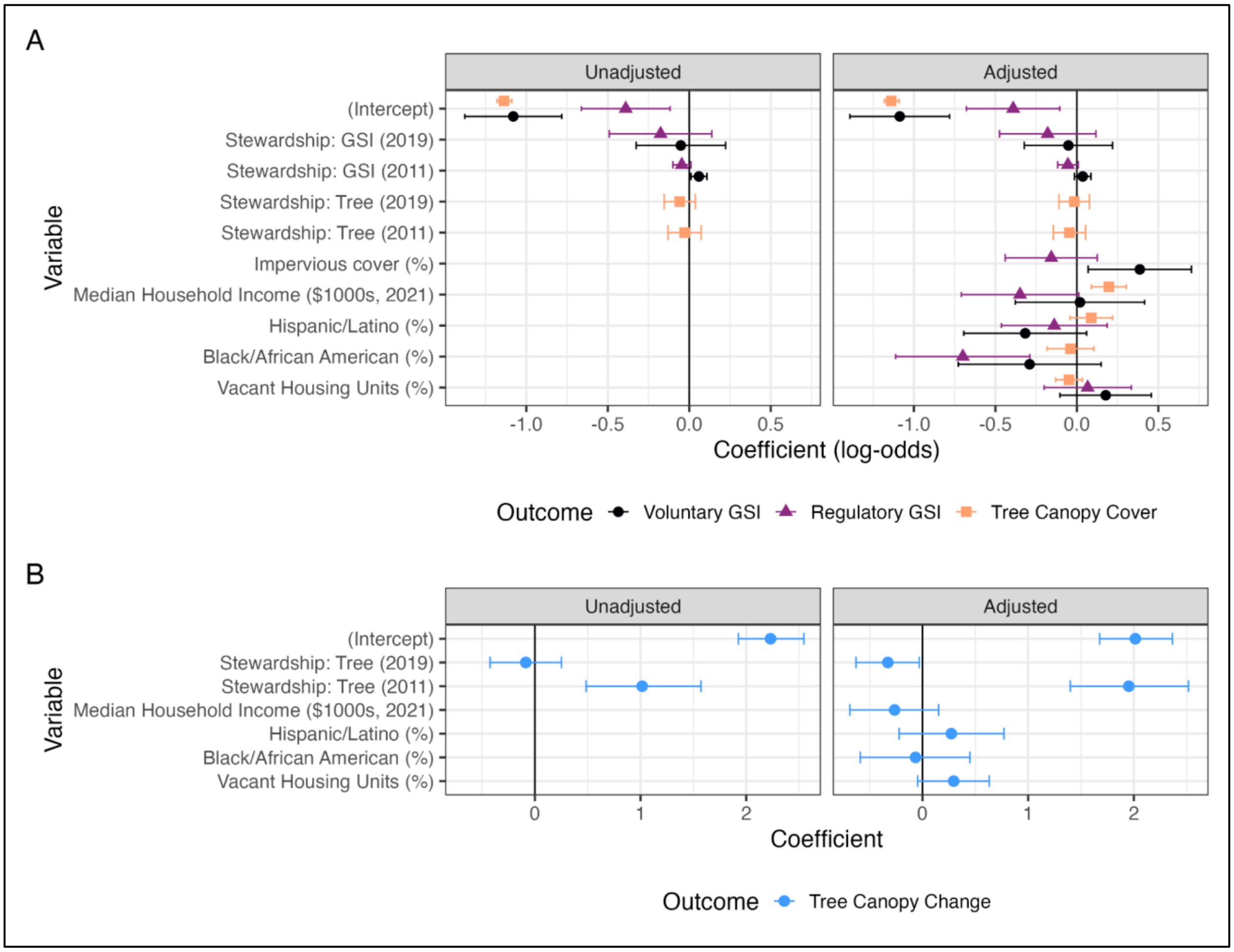

Figure 3. Besag-York-Mollié (Bayesian spatial regression) model coefficients for stewardship predicting 1) voluntary green stormwater infrastructure (GSI), 2) regulatory GSI, and 3) tree canopy cover (A), and tree canopy change (B). Stewardship represents the number of stewardship groups (filtered by site type and organizational focus) per square kilometer in 2011 and 2019, excluding city-wide groups. Unadjusted models contain the outcome and the predictor of interest, the adjusted models contain covariates. All models contain the spatially-autocorrelated random effects.

4. DISCUSSION

This study aimed to advance an *ecology for the city* (Pickett et al. 2016) by investigating spatial patterns and relationships between environmental stewardship, landscape characteristics, sociodemographic characteristics, and environmental outcomes (GSI and tree canopy cover) in Baltimore's neighborhoods and how these relationships develop and change over time. Indeed, we found some significant relationships between stewardship groups, sociodemographics, and spatial patterns of tree canopy cover and GSI that underlie the *ecology for the city* of Baltimore. Below we discuss implications of our research findings for interactions between social-ecological system components and the motivations, capacities, and challenges for stewardship organizations.

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The number of GSI-related stewardship groups in 2011 was found to be a significant predictor of the presence of voluntary GSI in our unadjusted model. As expected, there was more likely to be a relationship between stewardship and voluntary GSI compared to regulatory GSI, given that voluntary GSI were implemented by nonprofit organizations and community groups. However, the significant relationship between 2011 stewardship groups and voluntary GSI disappeared in our adjusted model, suggesting that some of the sociodemographic or environmental factors were contributing to the relationship we found. The inclusion of these covariates helped control for rival explanations, and in this case, those other factors appeared more tightly-related to the probability of GSI than the presence of GSI-related stewardship groups.

We observed a decrease in the number of stewardship groups reporting GSI and tree-related activities from 2011 to 2019. This change in responses may have impacted the lack of associations found between 2019 stewardship groups and tree canopy or GSI. While there is no conclusive explanation for the ~50% drop in reporting of GSI or working with trees between 2011 and 2019, we did observe that groups responded by listing fewer topics of focus in 2019 than in 2011, and we also observed that more groups claimed to work city-wide. These differences in organization responses suggest a narrowing of stewardship focus but broadening of geography that may have impacted our analyses.

Sociodemographic factors were not good predictors for the presence of voluntary GSI, but we did find that impervious surface cover was a significant predictor for the presence of voluntary GSI. The motivations and drivers for choosing voluntary GSI sites are likely caused by the needs and interests of partner groups involved with GSI design and construction (e.g., NGOs, neighborhood associations, and church groups), as well as physical neighborhood conditions. The siting process of bioswale installations within neighborhoods and block groups was examined in New Haven, CT, and the spatial analyses showed that most of the GSI installations were in low-income, high-impervious surface coverage areas that were also predominantly communities of color (Locke, Phillips de Lucas, et al. 2021). However, the mechanisms behind this pattern were not related to the socioeconomic makeup of the neighborhoods, but rather to the funder priorities, topography, areas experiencing frequent flooding, and where planners and engineers perceived the greatest need (Locke, Phillips de Lucas, et al. 2021).

While we found a positive association of voluntary GSI presence with impervious cover, our analysis does not allow an assessment of the volume of stormwater runoff that is treated by this interaction of GSI and impervious cover. However, this finding suggests that stewardship groups may be targeting high-impervious surface areas for stormwater runoff mitigation. Approximately 21% of voluntary GSI in the dataset were impervious surface elimination, while this type of GSI was only present in 0.2% of the practices in the regulatory GSI dataset (Solins et al. 2023). Further research is needed to understand and to quantify the potential for water quality improvement in Baltimore's neighborhoods based on the GSI's design characteristics (e.g., runoff treatment capacity) and the extent of water quality benefits provided by different types of GSI. Empirical data about surface area, storage volume, and runoff volume treated by each type of GSI could be considered to further evaluate the relationship between stewardship activity, impervious surface cover, and the capacity of stormwater treatment in neighborhoods where GSI is present.

We found that regulatory GSI was negatively associated with percent Black/African American population across Baltimore neighborhoods and was not significantly associated with median household income. These findings are both consistent with and contrary to previous analyses of this regulatory GSI dataset. Solins et al. (2023) found regulatory GSI to be less commonly present in block groups with predominantly Black populations and more commonly present in lower-income block groups. However, another study found no associations between regulatory GSI and race or income at the census block group scale in Baltimore (Baker et al., 2019). In Portland, OR, a higher green street density was observed in block groups with lower median income and higher percentage of minority groups (Chan & Hopkins, 2017).

Three explanations for the disparities between the prior results and our results are a) the Modifiable Areal Unit Problem or MAUP (Openshaw 1984), b) the way spatial autocorrelation was addressed or not, and c) the inclusion of stewardship groups as a primary predicting variable. The differences in the size, shape, and configuration of the Census block groups versus tracts versus neighborhoods may lead to different results. Scale and aggregation affect the results when using polygons (Openshaw 1984). The statistical problem of spatial autocorrelation can be addressed in several ways, here we adopted a Bayesian approach with unit-level autocorrelated random effects. Finally, and most importantly, our primary objective was to see how the presence of stewardship groups in 2011 and 2019, measured as the count per area relates to GSI, tree canopy, and tree canopy change, which the prior related studies did not include. These three differences explain the divergent results.

Land ownership also influences the spatial distribution of voluntary and regulatory GSI. At the census block group level, voluntary GSI projects were more than five times as likely to be located on public land when compared to regulatory GSI, reflecting the installation of regulatory GSI on private land after re-/development activities (Solins et al. 2023). Voluntary GSI on the other hand were often located on public land where there is space and a supportive landowner. Neighborhoods with vacant housing and aging infrastructure have been considered hotspots for nutrient pollution and water quality concern and, therefore, would greatly benefit from GSI installation (Hager et al. 2013). Vacant lots can quickly become overgrown and unkempt which may further signal disinvestment (Berland et al. 2020; Berland. et al 2023; Locke et al. 2017). Thus, vacant building removal can reduce crime (Locke et al. 2023) and create space for GSI, simultaneously improving stormwater management (Shuster et al. 2014; Shuster et al. 2022). However, we did not observe a significant relationship between vacancy and voluntary or regulatory GSI, which may reflect a lack of landowner support.

Green infrastructure is recognized as a viable nature-based solution to urban flooding, but could be implemented more widely and distributed more equitably. Based on the available regulatory and voluntary GSI datasets used in this study, approximately 71% and 62% of Baltimore's neighborhoods do not have any voluntary or regulatory GSI, respectively. Alternative investment approaches may allow for expansion of GSI practices into new areas. Community-based public-private partnerships programs are an approach to finance, design, construct, operate, and maintain GSI (US EPA 2018). Additionally, the long-term performance of regulatory GSI can be challenged by the lack of long-term maintenance programs and, consequently, these facilities may eventually become a burden to the community (Phillips de Lucas 2020). Thus, stormwater public-private partnerships can be an efficient strategy to overcome the challenges of implementing, maintaining, and ensuring the performance and longevity of the green infrastructure network. Stewardship may be a critical bottom-up component to implementing GSI through public-private partnership in environmental planning processes (Davies and Santo-Tomás Muro 2023) and may serve to promote ecosystem service provision by GSI (Cerra 2017). While stewardship organizations can play a role in community-based public-private partnership programs, there are considerable obstacles to their implementation. For example, Svendsen & Campbell (2008) identified a lack of financial resources and a lack of legal and business expertise in stewardship groups that can inhibit their effectiveness in community-based land management. Moreover, relying on private investment to fill gaps from declining public investment brings into question the efficacy of public-private partnership to contribute to urban sustainability goals (Lang and Rothenberg 2017).

We found that the number of environmental stewardship groups related to trees in either 2011 or 2019 were not good predictors of 2018 tree canopy cover, but 2011 stewardship groups were significantly associated with tree canopy change from 2013-2018. More groups co-occurred with net canopy increases. A previous study found 1.16% greater tree canopy cover (assessed in 2007) with each additional stewardship organization in Baltimore neighborhoods (Romolini et al., 2013). Another previous study found that there was a significant relationship between the number of stewardship organizations and the change in vegetation in New York City neighborhoods; more groups coincided with increases in vegetation cover (Locke et al., 2014). These studies looked at the relationship between tree canopy or vegetation cover, respectively, and all environmental stewardship groups. It is possible that by selecting for tree-focused groups and removing citywide groups we excluded some stewardship actions that impact tree canopy at the neighborhood scale. But including citywide groups would have rescaled the estimates without actually adding any new information; all neighborhood counts would have been increased. Furthermore, although we focused on stewardship groups that care for trees, we lack information about the specific activities they perform and at what scale within each neighborhood. Such activities might include tree pruning, watering, mulching, invasive plant removal, advocacy, and conservation of forest patches that may impact tree health and canopy cover in addition to tree planting. Thus, follow-up surveys and/or interviews could be conducted for a better understanding of what and how stewardship activities were contributing to the conservation and growth of tree canopy cover. Additionally, small newly-planted trees resulting from recent stewardship activities may not yet have been captured by the remotely sensed imagery, framing the importance of continued longitudinal studies.

We observed a significant positive relationship between median household income and tree canopy cover, a relationship that has been documented before in Baltimore (Troy et al., 2007) and many other cities worldwide (Gerrish & Watkins, 2018). However, historical demographics may be a better predictor of present-day vegetation (Boone et al., 2010; Locke & Baine, 2015), implying that historical stewardship activity (from many decades ago) may also have had an impact on present-day tree canopy. The addition of temporally-lagged stewardship group activity predicting tree canopy adds to the literature about temporal dynamics of urban forestry stewardship. Specifically, neither the 2011 or 2019 groups were associated with 2018 tree canopy, while 2011 tree-related groups were positively associated with increases in tree canopy from 2013 to 2018. The many social, biological, political, and economic forces that impact urban tree canopy cover over decadal timeframes may make it challenging to identify patterns between ephemeral and dynamic stewardship actions and long-lived trees (Grove et al. 2018; Locke, Hall, et al. 2021; Roman et al. 2018). It is therefore particularly noteworthy that 2011 groups were significantly related to tree canopy increases at the neighborhood scale because a five-year (2013-2018) timestep is relatively short. Yard-scale analyses of the same tree canopy change data did not reveal significant net changes at that spatial scale (Locke et al. 2025). There was also a significant negative association between 2019 tree-related stewardship groups and 2013-2018 canopy change. While it is difficult to interpret this finding without additional data about the groups' motivations and activities, it is possible that groups were motivated to establish and or expand work into neighborhoods experiencing tree canopy loss.

More in-depth research is needed to understand how stewardship organizational motivations, capacities, and challenges for tree planting programs and implementation of GSI projects impact whether these practices are distributed effectively and equitably. For instance, tree giveaways from TreeBaltimore and rain barrel programs had higher uptake in higher income and white neighborhoods, as well as those that had greater residential tree canopy cover (Locke and Grove 2015; Locke and Grove 2016). Additionally, residents' values, perceptions, and cooperation towards urban trees and green infrastructure also affect the outcome of tree planting and GSI projects. For instance, residents of East Baltimore have been opposed to tree-planting programs in their neighborhoods since the 1960s (Battaglia et al. 2014). Similar ambivalent feelings related to urban forest patches have also been observed in Baltimore neighborhoods (Sonti 2020). Working to acknowledge and address residents' negative perceptions and priorities may improve the success of community greening initiatives while strengthening community engagement and empowerment.

In addition to stewardship presence, the city's environmental stewardship network structure (e.g., density, centralization, etc.) can influence information and knowledge distribution as well as the application of decentralized management practices (Romolini 2016). For instance, information on new technologies and sustainable management practices often flows through informal social ties rather than formal institutional structures (Bouwer, Pasquini, and Baudoin 2021; Isaac et al. 2007).

5. CONCLUSIONS

Cities are complex social-ecological systems, and understanding the relationships between biophysical, social, and built components plays an important role in identifying inequities in environmental outcomes and informing planning for urban resilience. In this study, we found that 2011 GSI-related stewardship groups were positively associated with the presence of voluntary GSI. Interestingly, while we found that 2011 tree stewardship groups were positively associated with future tree canopy net gains, there was also a small negative relationship between 2019 tree stewardship groups and tree canopy change (assessed from 2013-2018), suggesting the need to better understand the motivations that underlie spatial relationships. A small but significant relationship between 2019 tree stewardship groups and net canopy decline warrants additional investigation. Additionally, percent impervious cover was positively related to the presence of voluntary GSI, while the percent Black/African-American population was negatively related to the presence of regulatory GSI. Stewardship groups create actions that can vary by demographics and spatial characteristics with the potential to contribute to environmental outcomes. Our study demonstrates that these outcomes often lag behind stewardship actions, such that point-in-time snapshots may not reveal the relationships between stewardship and ecological outcomes in urban spaces. Moreover, conducting more in-depth research about the specific activities, motivations, and political factors that influence stewardship groups related to trees and GSI, and community values and perceptions towards these nature-based solutions, may help improve rates of establishment, maintenance, and performance over time.

Supplemental Table 1. Organizational characteristics of environmental stewardship groups from 2011 and 2019 STEW-MAP surveys.

	2011 Tree Stew Groups	2019 Tree Stew Groups	2011 GSI Stew Groups	2019 GSI Stew Groups
Organization Type				
Non-Profit / Community Group	77% (86)	70% (48)	71% (46)	58% (14)
Public	0	13% (9)	11% (7)	13% (3)
Private	2% (2)	1% (1)	3% (2)	8% (2)
Other	13% (15)	16% (11)	15% (10)	21% (5)
Full-Time Staff				
Mean	16	5	25	5
Min	0	0	0	0
Max	350	50	350	37
Part-Time Staff				
Mean	7	6	9	3
Min	0	0	0	0
Max	135	300	135	15
Members				
Mean	227	62	256	61
Min	0	0	0	0
Max	3000	780	3000	284
Regular Volunteers				
Mean	24	54	29	117
Min	0	0	2	0
Max	150	2000	150	2000
Year Founded				
Mean	1984	1990	1988	1997
Min	1797	1888	1797	1949
Max	2011	2019	2011	2018

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