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ARTICLE

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Distributed urban forest patch sampling detects edge effects and woodland condition for monitoring and management

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Abstract

Urban forest patches, including woodland interiors and bounding edge habitat, result from secondary succession and fragmentation of more extensive forested landscapes in the eastern United States. Management regimes, surrounding land use, and successional processes lead to distinct environments and contribute to local and regional heterogeneity. However, many woodlands are degraded due to frequent disturbance, aggressive exotic species, and heavy browsing, which stress canopies, reduce regeneration, and may reduce ecosystem services. Effective management requires rapid, repeatable assessment of forest composition, structure, and condition at the scale of local decision-making. We present and apply a protocol for characterizing urban woodlands that generates new insight into the status of urban woodlands and baseline data for change detection over time. Samples of overstory composition, ground cover, surface soil measurements, and the Schumacher Vine Encroachment Index were collected at 845 points across each of 47 patches across Baltimore, Maryland. Simple citywide summaries allowed characterization of Baltimore's urban overstories as overwhelmingly native, though dominated by a range of successional conditions. By contrast, we found that ground layers were predominantly exotic, with abundant invasives or ruderal native species benefiting from disturbed conditions. Seven overstory types were distinguished, the majority under threat from aggressive vines. Most soils showed little evidence of compaction, but variable organic content. Distributed data allowed cross-patch comparison as well as within-patch analyses along edge-to-interior gradients. Species diversity, nativity, and overstory basal area all increased toward woodland interiors, whereas soil compaction and vine encroachment decreased. Structural and compositional shifts in both overstory and ground layer species revealed indicators of edge (15.2–18.7 m) and interior (>41.5 m) conditions, as well as evidence of transitional zones with distinct patterns of biodiversity. Despite high levels of fragmentation and disturbance that challenge municipal land managers operating with limited resources,

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rapid, low-cost sampling enabled comparison across multiple scales, encouraging repeated sampling and adaptive response to changing forest conditions. Qualitative and quantitative analysis as well as specific examples illustrated the generic utility of the protocol for a range of applications and its ability to produce new insight enabling management action and informed conservation planning.

KEYWORDS
distributed sampling, edge effects, forest patches, monitoring, Schumacher Vine Encroachment Index, urban forestry, wedge prisms

INTRODUCTION

Background

The majority of urban trees in the eastern United States are found in patches of naturally regenerating woodlands across public and private lands (Nowak, 2020; Pregitzer, Ashton, et al., 2019). As a subset of the urban tree canopy that includes street trees, parks, managed yards, urban, and suburban forest patches exist as small areas of contiguous tree canopy and naturally regenerating understory vegetation with distinct mosaics of ownership, land use history, and management practices (Johnson et al., 2020). Urban forest patches also exist within the larger context of the region, which has undergone centuries of intense logging and land clearing for agriculture, followed by 150 years of natural reforestation prior to more recent development pressures (Thompson et al., 2013).

Within the northeast corridor (i.e., Boston to Washington megalopolis), cyclical patterns of land clearing and regrowth have led to progressive net fragmentation of once extensive forests into woodland patches resulting from distinctly different processes (Matlack, 1994; Zhou et al., 2011). Some occur on abandoned agricultural lands that subsequently experience no further development, some in areas with terrain too difficult to have been farmed or developed for human settlement, and some may occur on previously developed acreage (e.g., Trammell et al., 2020). Dynamic and variable combinations of management regimes, adjacent land uses, land use histories, and successional processes may lead to distinct environments and subsequent shifts in species composition within both woodland interiors and surrounding edges that contribute to regional heterogeneity and biodiversity.

Fragmented woodland perimeters may be maintained through active management or by gradual transitions from surrounding land uses, and studies have emphasized the importance of edge effects as a transition zone for the maintenance of forest interiors (Cadenasso et al., 1997; Matlack, 1993). Although much study has focused on surrounding land cover, the nature of these transitions and their effects on overall woodland character (Guirado et al., 2006; Jin et al., 2020; Smith et al., 2018; Vallet et al., 2010), relatively little study has focused on characterizing the extent of edge effects within urban contexts, even as such habitats become increasingly prevalent (but see Jin et al., 2021; Li et al., 2018; Reinmann & Hutyra, 2017).

Urban Forest management

Like many cities, Baltimore has implemented an ambitious campaign to increase the city's tree canopy to meet sustainability goals (Shcheglovitova, 2020). Baltimore has comparatively greater canopy cover (34%) than northeastern U.S. cities like New York City (20%) or Philadelphia (19%) (Morzillo et al., 2022). However, only ~22% of its tree canopy is in forest patches (Avins, 2013). Urban forested natural areas are often assumed to require little management, have fewer resources dedicated to their care, and are less often subject to policy and planning efforts than street trees or those in landscaped areas (Forgione et al., 2016; Johnson et al., 2020). Yet, without management interventions, urban woodlands are likely to degrade due to a combination of frequent disturbance, aggressive competition from exotic species, and herbivory, all of which can damage native canopy trees and prevent regeneration in the understory (Aronson & Handel, 2011; Templeton et al., 2019).

Effective management of forested natural areas for climate resilience, heat island mitigation, stormwater absorption, and other ecosystem services requires that municipalities and communities be able to rapidly assess forest composition, structure, and condition at the scale of local decision-making. Such characterizations can inform the prioritization of management actions within or across property parcel boundaries, as well as long-term

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policy goals for citywide or regional sustainability (Morzillo et al., 2022). Furthermore, the characterization of forest conditions must be repeated at regular intervals to monitor changes in forest composition and structure, assess restoration treatments, and detect the emergence of new social or ecological threats.

Conventional woodland sampling

Fine-scale, spatially explicit, quantitative data on vegetation composition and structure are critical to producing actionable information for urban natural resource managers. Many agencies or conservation organizations begin their management efforts by collecting qualitative data about forest conditions (Avins, 2013; Lautar, 2020; Morzillo et al., 2022; Rogers & Rowntree, 1988). Although this information may be collected rapidly, it is often difficult to analyze, interpret, or apply across scales. Citywide assessments have become widespread tools for tracking urban forest change over time and informing broad-scale policy (Pregitzer, Charlop-Powers, et al., 2020) but are not designed to capture fine-scale information needed to manage individual forest patches (Edgar et al., 2020). As a result, some managers have stratified their sampling effort to target areas of interest (e.g., urban forested natural areas; Pregitzer, Charlop-Powers, et al., 2020). This approach produces substantial amounts of high-quality data that quantitatively characterize conditions (e.g., stand basal area, stem density, percent native species) within plots and are often extrapolated to estimate forest conditions of remaining areas under study (e.g., Nowak, 2020). However, plot-based data collection over broad areas requires a large amount of effort by skilled practitioners and is not designed to capture gradients or variation within individual woodlands. Because they have edges, because they are exposed to high levels of disturbance and exotic introductions, and because their impacts can vary with ownership and land use history at the level of individual parcels, widespread yet explicit information is needed to manage urban forest patches.

We suggest that urban woodlands can be sampled with a distributed approach to capture edge-to-interior gradients of vegetation and environmental conditions within each patch or management unit (e.g., Bergès et al., 2013; Godefroid & Koedam, 2003; Trammell et al., 2020). Transect-based sampling has been used to describe vegetation along gradients, but unless the gradients are known ahead of time and transects are placed deliberately (e.g., Baker & Wiley, 2004) they often miss local heterogeneity. By contrast, systematically distributed, point-based sampling can capture multidirectional gradients in biophysical conditions without advanced knowledge.

Data needed for management

Not many cities consider the contribution of existing canopy to green policy goals, focusing instead on planting new trees (Forgione et al., 2016; Morzillo et al., 2022; Shcheglovitova, 2020). Understanding canopy extent, at a minimum, allows city managers to consciously choose whether to retain existing stands or plan development to accommodate extant woodlands. More explicit discretization and disambiguation of *canopy* (i.e., the presence of trees) into *hard* (i.e., over hard/impervious surfaces) and *soft canopy* (i.e., over pervious/natural surfaces) (Alonzo et al., 2021) as well as *forested natural areas* (i.e., closed canopies with natural regeneration and pedogenesis) is increasingly recognized as having value for urban management (Johnson et al., 2020; Phillips et al., 2019; Pregitzer, Ashton, et al., 2019).

One often overlooked attribute of forested natural areas can be well preserved and functioning soil profiles. Understanding the age and structure of woodland soils can assist cities with evaluating their capacity and value in providing ecosystem services, including regeneration (Pregitzer et al., 2016). Soil bulk density and organic content may relate to a site's ability to filter and/or retain stormwater (e.g., Phillips et al., 2019), sequester carbon (Pouyat et al., 2009), or absorb nutrients (Ward et al., 2020). Additionally, understanding where there are healthy, well-preserved soils within and among forest patches could have important implications for carbon and nutrient dynamics as well as the soil microbiome (Charlop-Powers et al., 2016. Cities might deliberately manage the retention of forests with healthy soils to support long-term climate resilience.

Native and nonnative plant species, in the overstory or ground layer, affect successional trajectories and may have distinct phenologies or wildlife value, so understanding their distribution across a city can help establish priority management areas or preserve endangered populations. In contrast with a conventional sample plot, such information is relevant throughout an entire patch, spanning edge-to-interior gradients and multiple scales of analysis. On a neighborhood level, understanding the native species in a particular patch or set of patches can drive decisions about where to target removal efforts of invasive exotics or to facilitate native species in conservation and/or restoration. Citywide, understanding the distribution of different woodland conditions along with their spatial configuration can help city managers develop better budget estimates for long-term woodland care. Distinguishing patches of high wildlife value or other ecosystem services relative to soils or vegetative composition and structure can help establish management priorities or argue for budget adjustments to achieve sustainability goals.

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We set out to develop and apply a rapid and cost-conscious protocol for characterizing urban woodlands to inform monitoring and management efforts across Baltimore City. The sampling protocol has been developed into a user-friendly guide and is available online (Baltimore Green Space, 2020). Key metrics included systematic and distributed estimates of overstory and ground layer vegetation composition, as well as overstory basal area. Based on our previous experience in Baltimore's urban woodlands, we were especially concerned about tracking the distribution of exotic species, the predominance of aggressive vines and lianas, and understanding how soil conditions were related to distributions of the above factors in edge versus interior woodland spaces. Our goal was to collect this information, demonstrate its potential to generate useful new insight into the status of Baltimore's urban woodlands consistent with efforts in other eastern U.S. cities, and provide baseline data for change detection over time.

METHODS

Study area

Like many cities of the Mid-Atlantic United States, Baltimore straddles the fall zone between the Upper Piedmont and Coastal Plain physiographic provinces. Regional soils and potential natural vegetation in Maryland were described by Brush et al. (1980). Much of northern and western Baltimore City consists of highly weathered and nutrient-poor alfisols and ultisols, with overstory dominants ranging from Chestnut and Post Oak associations on xeric, rocky soils to Tulip Poplar-Beech-Basket Oak associations on more mesic sites. Bottomland assemblages dominated by Sycamore-Green Ash-River Birch also occur within ravines and gorges that dissect the city, including those of Gwynns Falls, Jones Falls, Gunpowder Falls, and Herring Run.

Following western European settlement during the 17th century, forests of the region experienced nearly complete clearing by the end of the 18th century (Benitez & Fisher, 2004; Zhou et al., 2011). Migration to midwestern and western territories during the mid-19th century and post-Civil War population shifts led to moderate secondary afforestation, yet displacement of urban populations to suburban lands after World War II rejuvenated clearing, further isolating remaining woodlands (Zhou et al., 2011) and stretching under-resourced budgets. There is currently an urgent need for extensive information about the location of forest patches as well as for explicit information regarding their condition.

Field sampling

Site selection

Beginning as a survey of 12 eased properties, subsequent sampling was expanded to encompass a broader representation of woodlands in a spatially balanced design across both regional (i.e., across the fall zone) and local (i.e., uplands vs. bottomlands) physiography (Figure 1). Our sample was derived from a map of forest patches (Sonti et al., 2024; Sonti & Baker, 2023) developed from 2015 high-resolution (0.37 m^2) land cover (O'Neil-Dunne, 2017) that explicitly avoided overrepresentation by city parklands. We focused initially on larger woodlands or woodland segments (i.e., >0.5 ha) to ensure adequate samples of both edge and interior canopies, though occasionally sampling points included smaller areas of edge or isolated canopy either around the periphery of larger patches or as targeted efforts.

Distributed point location

For each selected woodland area, the approximate extent of the canopy was identified in Google Earth imagery

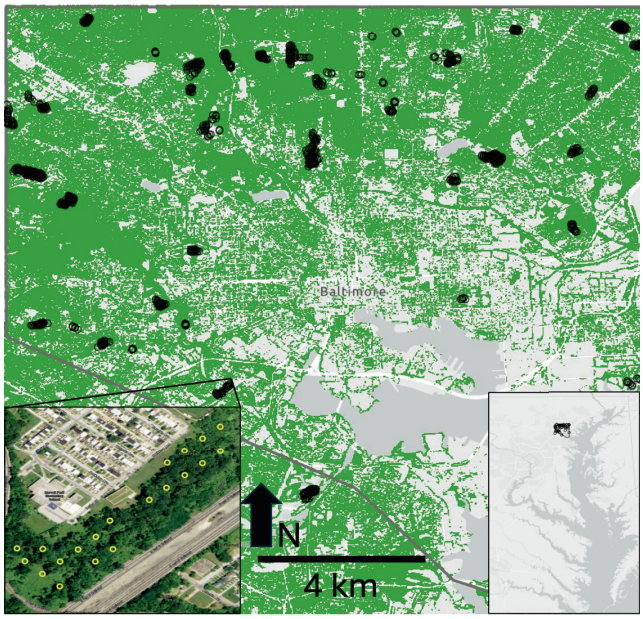

FIGURE 1 Woodland patch sample point locations (black circles) within the city of Baltimore, Maryland, USA, relative to 2015 urban tree canopy (green). Right inset shows the location of Baltimore (black) relative to the Chesapeake Bay along the Atlantic coast. Left inset shows an example of how each patch was sampled systematically with points 35–40 m apart, resulting in 845 samples across 47 patches throughout the city. *Source*: Imagery Google Earth.

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and overlain with a grid of sampling points spaced by 35–40 m. Coordinates for each point and the relative orientation of the grid were recorded, including a set of candidate points outside of the canopy for reference and orientation in the field. A handheld GPS unit was used to locate reference points, whereas subsequent points were located by a combination of the GPS unit or compass, and field tapes. Occasionally, points mapped from imagery within the canopy were found to occur over hard surfaces or in gaps and were not sampled for soil and groundcover or overstory, respectively.

Vegetation sampling

At each point, overstory relative dominance was estimated using a 10 Basal Area Factor (BAF) prism. Gauged for a certain stocking density (e.g., each stem recorded as "in" is counted as representing 2.29 m^2 ha^{-1} [10 ft^2 $acre^{-1}$]), prisms may be used to estimate stand basal area (usually when averaged over >2 samples) or relative dominance, providing improved integration of spatial heterogeneity over fixed-area plots (Baker & Wiley, 2004). Overstory stems viewed through a prism held horizontally at the center of a circle were included if any refracted portion at breast height (1.37 m) overlapped with unrefracted portions above or below the prism. Practically speaking, this means that larger stems could be farther away and still be included, whereas smaller stems would only be counted if they occurred very close to the sample point. All woody stems (i.e., trees, shrubs, and vines) included at a prism point were identified to species, enumerated, and rated on the Schumacher Vine Encroachment Index, which tracks the degree of vine growth on individual overstory stems (Figure 2). In the ground layer, a 1-m^2 quadrat developed from PVC was placed randomly within 1.5 m of each point. All species (woody and herbaceous) below 1 m in height were assessed for percent cover. For ease of interpretation and quantification in the field, all percent cover, including bare ground, was required to sum to 100. In practice, such a requirement may have led to overestimation of the areal coverage of less abundant and low-lying plants or taller plants when they occurred over a carpet of creeping vines or smaller herbs.

Soil sampling

For each quadrat, five penetrometer readings were averaged to estimate soil compaction; one at each corner of the quadrat frame and one near its center. Penetrometer tips were selected based on soil moisture, with a 1.9-cm (3/4-inch) wide tip used for moist soils and a 1.27-cm (1/2-inch) tip for dry soils. The same individual collected penetrometer readings for any given woodland to ensure consistency. A soil punch with a 2.5-cm-diameter stainless steel sampling probe was used to extract a 20-cm surface soil profile, no further than one meter away from each prism point. The depth, Munsell Soil Color, and texture (by feel) of different layers in the 20 -cm soil sample were recorded, along with the depth of the O horizon, if present.

Bulk density of the mineral soil was estimated by removing a 5-cm-diameter by 5-cm-deep core with a soil hammer in or near the quadrat, no further than one meter away (Blake & Hartge, 1986). Soil samples were bagged, brought back to the lab, and refrigerated at 4°C until analysis. Organic matter content of the mineral soil was determined by loss-on-ignition (360°C for 1 h). In addition, a 1.4-m soil auger with a 10.2-cm-diameter bucket was used to describe a representative soil profile at least once for each woodland, as a contextual reference for interpreting distributed samples. Woodlands with variable physiography might have two or more representative profiles. Horizons for each profile were described, and the entire set was photographed. Once back in the lab, all field data were transferred into a digital relational database with a predefined structure.

Analysis

Citywide summary statistics

Initial analyses were focused on describing citywide woodland characteristics to demonstrate comparability with products of plot-based samples. Prism point overstory sampling allowed calculation of point-based species richness, Shannon diversity, basal area (here square meters per hectare), and mean Schumacher index scores. Ground layer quadrats allowed for the characterization of species richness, growth form, Shannon diversity, and relative abundance measured as percent coverage. Soil samples yielded mean penetrometer readings, soil bulk density, and percent organic matter. Distributions of all measured variables across all sampling points were examined using histograms, density plots, box-and-whisker plots, or violin plots (R package *ggplot2*; Wickham, 2016). For continuous and ordinal variables, we assessed the magnitude and variation of observed values. For compositional variables in both prism points and groundcover quadrats, we developed charts of mean relative dominance or abundance across all points, then summarized proportions of native and exotic species. All analyses were performed using the statistical language R (R 4.4.2, R Core Team, 2024).

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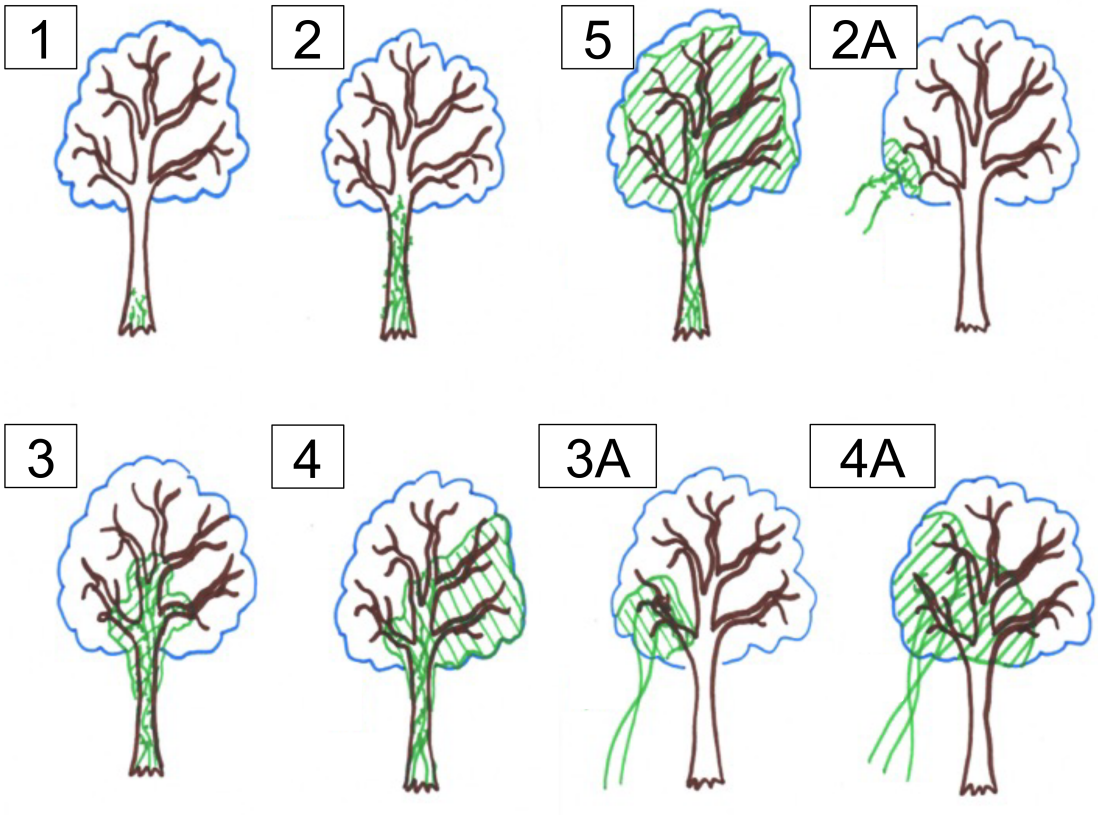

FIGURE 2 Schumacher Vine Encroachment Index. Scores range from zero to five (0–5) with zero (0) indicating no vines present on the base of the tree, one (1) indicating vines at the base of the tree, two (2) indicating vines on the trunk, three (3) indicating vines reaching the base of the canopy, four (4) indicating vines over more than 50% of the canopy, and five (5) indicating vines over more than 90% of the canopy. Scores of 2A, 3A, or 4A indicate special cases in which vines reach a tree from a neighboring canopy.

Subsequent analyses were concerned with describing compositional variation among sample points. Overstory relative dominance and ground layer percent coverage, analyzed separately, were used to develop hierarchical cluster dendrograms using Ward's Method on Bray–Curtis (Sorenson) dissimilarity (Bray & Curtis, 1957; Legendre & Legendre, 2012). Agglomerative clustering grouped sample sites based on their assemblage dissimilarity, whereas Ward's method minimized within-group variance to generate distinct cluster membership. Cluster membership across 3 to 12 partitions was assessed using indicator species analysis (Dufrêne & Legendre, 1997) to identify the most distinct groupings using cluster indicator value (IndVal) scores. IndVal scores describe the degree of association of a particular species to each cluster group as the product of its abundance in a particular habitat type relative to others (i.e., *specificity*) and occurrence frequency within that type (i.e., *fidelity*). Although statistically significant IndVal magnitudes may be obtained when observed scores exceed those obtained by chance alone, only significant values larger than 25 were reported because smaller values tended to repeat species associations across cluster groups. Pie charts were used to visualize mean relative dominance in each overstory cluster or mean percent coverage in each ground layer cluster. We also performed nonmetric multidimensional scaling (NMDS; R package *vegan*; Oksanen et al., 2013) as a complement to cluster analysis to better visualize compositional similarity among samples and their cluster membership.

Among patch characterization

Within the broader context of Baltimore, a second level of analysis focused on comparing individual woodland patches and their characteristics. Cluster membership for each point was summarized across woodland patches using bar charts as a form of crosspatch comparison. Bar charts of edaphic properties, mean Schumacher scores, overstory basal area, and diversity metrics were used to summarize and further compare patch characteristics. These comparisons were important for establishing a baseline for future management and the range of conditions included in the sample. However, crosspatch

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comparisons highlighted a need for further stratification associated with edge-to-interior gradients.

Within-patch characterization

Within each woodland patch, the most obvious and ubiquitous source of variation in the field among sample points was the difference between edge and interior conditions. Changes in the magnitude or variance of a response variable across an environmental gradient were assessed with nonparametric changepoint analysis (nCPA; King & Richardson, 2003). nCPA finds a split point within a set of ordinal (ranked) observations that leads to the greatest reduction in deviance among samples. Uncertainty associated with the location of the changepoint is assessed with a bootstrap resampling procedure. We used nCPA to detect distances from woodland edges that resulted in a change in metric values such as the basal area of overstory stems, the proportion of exotic species, or species richness. Based on field observation of canopy gaps within woodland interiors, we quantified responses using distance from exterior woodland edges as measured from the edge of a canopy from a 2015 land cover map (O'Neil-Dunne, 2017). A Wilcoxon unpaired two-sample test was used to assess values on either side of the observed changepoint for significant differences in mean values.

Compositional changes along edge-to-interior gradients for both overstory and ground layers were assessed with threshold indicator taxa analysis (TITAN; Baker & King, 2010; Baker et al., 2015). TITAN works similarly to nCPA in that it finds split points in the abundance and occurrence of each species along an environmental gradient. Instead of reducing deviance, TITAN finds the greatest change in each species' distribution along any environmental gradient using IndVals normalized (as z scores) to observed patterns of abundance through a permutation procedure. Uncertainty in each species' changepoint is assessed by bootstrap resampling and used to quantify the *purity* (i.e., response direction) and *reliability* (i.e., response contingency) of each indicator species. The z scores of pure and reliable indicators were summed to derive an estimate of community change along the environmental gradient, where larger values and distinct maxima were interpreted as indicators of a threshold (Baker & King, 2010; 2013).

Based on our analysis, we compared and contrasted species-area relationships in woodland edges, interiors, and transitions using the *rarefy* function in package *vegan* (Oksanen et al., 2013). Rarefaction assessed uncertainty in the accumulation of species richness over increasing sample areas as a function of the order of samples. We compared richness associated with different plant forms, including overstory trees, woody shrubs, vines and lianas, and ground layer herbs.

RESULTS

Citywide summaries

We evaluated overstory and groundcover species composition, vine encroachment, and soil compaction at the city extent. The sample consisted of 845 points distributed (per-patch range: 3–72, IQR: 7–30, median: 15, mean: 18) across 47 woodlands throughout the city (see Appendix S1: Figure S1). Over 47 patches, mean and median basal area were 16.2 and 16.1 $m^2\ ha^{-1}$ (range: 2.3–39.0, IQR: 9.9–21.4), respectively. Overstory composition was overwhelmingly native, with half of the sampled points entirely native and 90% of points consisting of more than 75% native trees (Figure 3A). Baltimore's overstory canopy was dominated by the early successional tulip poplar (*Liriodendron tulipifera*), followed by the state tree, white oak (*Quercus alba*), understory tolerant northern red oak (*Quercus rubra*), red maple (*Acer rubrum*), American beech (*Fagus grandifolia*), and green

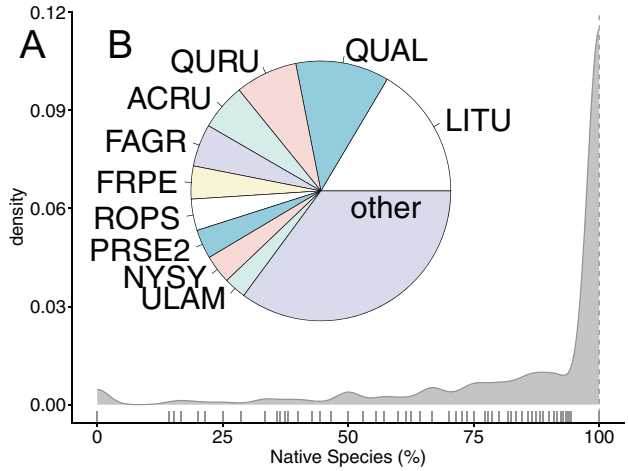

FIGURE 3 Composition of urban forest patches in Baltimore, Maryland, USA, showing (A) probability density of native overstory as a proportion of all sampled stems across 845 prism points and (B) relative dominance of the ten most dominant overstory species using USDA species codes. In (A), samples are plotted as a vertical rug along the x axis, whereas the median value is shown by a dashed line. In (B), species codes include tulip poplar (LITU), white oak (QUAL), northern red oak (QURU), red maple (ACRU), American beech (FAGR), green ash (FRPE), black cherry (PRSE2), black locust (ROPS), black gum (NYSY), and slippery elm (ULRU). The proportions of remaining species are grouped into an "other" category.

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ash (*Fraxinus pennsylvanica*). These six species constituted >50% of the sampled overstory (Figure 3B), suggesting potential for broad overlap in overstory composition.

Hierarchical cluster analysis revealed a strong contrast in high-order species compositional structure between several types of forest overstory samples (Figure 4A). The entire sample set showed evidence of seven cluster types. On the right side of Figure 4A, about one-half of the samples fell into well-organized groups of relatively distinct assemblage types, each consisting of two or three subgroups. By contrast, the other half of the samples on the left side of Figure 4A displayed less evidence of hierarchy and a higher degree of "chaining" with smaller groups agglomerating over a broad range of dissimilarities, indicative of less distinct and less consistent compositions. These interpretations were partially corroborated through ordination of sites in species space and exploration of cluster relative dominance, which suggested clusters 1ElmAmur (i.e., *Ulmus* and *Lonicera maackii*) and 2Locust (i.e., *Robinia*) were associated with higher levels of disturbance-adapted species and

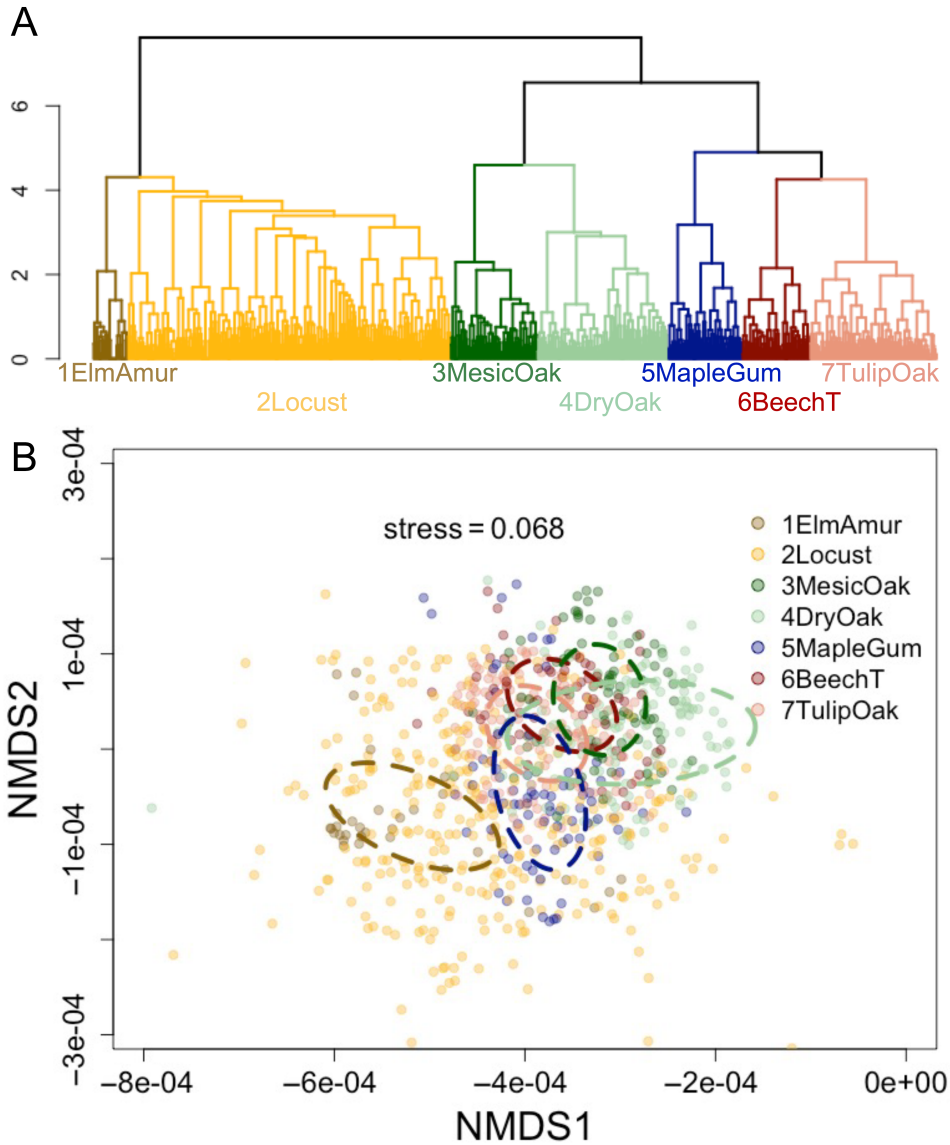

FIGURE 4 Compositional structure of 845 overstory prism points in urban forest patches in Baltimore, Maryland, USA, showing (A) hierarchical cluster dendrogram (Ward's method) based on Bray–Curtis dissimilarity and (B) nonmetric multidimensional scaling (NMDS) ordination of the same samples reduced to two dimensions. In (A), the seven clusters at height = 4.1 were most distinct based on indicator species analysis, whereas their compositional dissimilarity is illustrated by the ordination in (B). In (B), distinctions among clusters are somewhat difficult to discern due to compression of ordination space due to broad variability in cluster 2Locust (not all points shown). SD ellipses of remaining clusters indicate separation with increasing moisture availability from right to left and later successional stages from bottom to top.

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nonnatives, whereas the other five types were distinguished primarily by moisture availability and successional stage (Appendix S1: Figure S2).

Two-dimensional NMDS ordination (stress = 0.068) revealed species space entirely dominated by a high degree of variation and highly unusual samples belonging primarily to clusters 1ElmAmur and 2Locust. To adequately assess variation within and among the remaining clusters, about 20 2Locust outliers with anomalous species composition (i.e., entirely or mostly nonnative) were ignored for display purposes (Figure 4B). Closer inspection revealed substantial overlap in species composition among cluster types, some of which was expected after clustering. SD ellipses indicated some separation among clusters associated with trends in moisture availability and successional stage. However, the overlap suggests clusters had many species in common and that distinctions were likely driven by relatively subtle differences in relative dominance or the predominance of subdominant associates (Appendix S1: Figure S2). This was especially true because most patches contained more than two cluster types, making intermediary compositions more likely (Appendix S1: Figure S3). Corroborating the cluster dendrogram and NMDS, multivariate distance to centroid (i.e., spatial median) permutation comparisons indicated that cluster 2Locust was significantly ($p < 0.001$) more dispersed than the other six, with clusters 1ElmAmur, 5MapleGum, and 4DryOak more dispersed than clusters 3MesicOak, 6BeechT, and 7TuilpOak.

Although nearly 30% of prism points fell within 20 m, and 47% fell within 40 m of a woodland edge (Appendix S1: Figure S4), most clusters showed similar distance distributions, with fewer than 25% of points falling within 25 m of an edge (Appendix S1: Figure S5). However, both 1ElmAmur and 2Locust, making up nearly half of the samples, occurred significantly closer to edges than other clusters, with more than 40% of their points within 25 m of canopy edges. Given their predominance of ruderal or nonnative species (Appendix S1: Figure S2) and proximity to woodland edges, 1ElmAmur and 2Locust may simply represent disturbed versions of other types found more commonly in woodland interiors.

Analysis of groundcover composition revealed greater nonnative species proportions than overstory samples, although samples also exhibited greater degrees of compositional variation (Figure 5). More than half of the sampled quadrats contained less than 25% native species cover; the most ubiquitous species were nonnative and

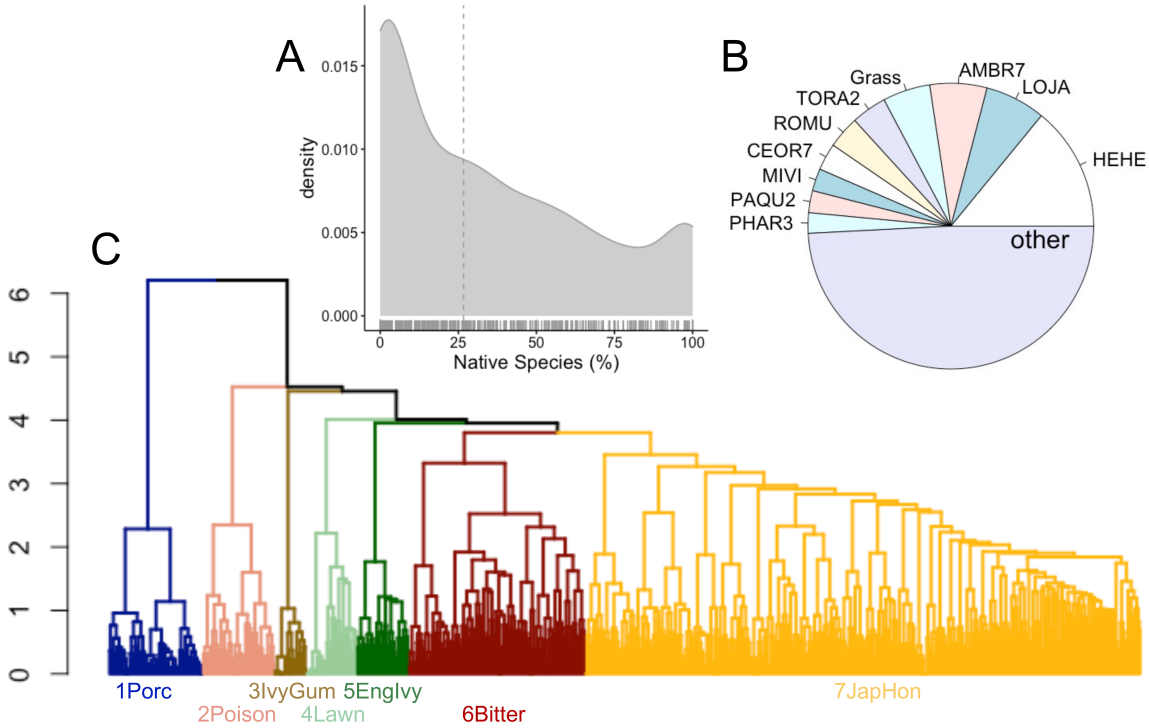

FIGURE 5 Composition of urban forest patches in Baltimore, Maryland, USA, showing (A) probability density of native ground cover as a proportion across 736 1-m^2 quadrats; (B) relative abundance of the ten most common species using USDA species codes including: English ivy (HEHE), Japanese honeysuckle (LOJA), porcelain berry (AMBR7), turfgrass (GRASS), poison ivy (TORA2), multiflora rose (ROMU), Oriental bittersweet (CEOR7), Nepalese browntop (MIVI), Virginia creeper (PAQU2), and reed canary grass (PHAR3), whereas remaining species making up approximately 50% of relative abundance; and (C) hierarchical cluster dendrogram (Ward's method) based on Bray–Curtis dissimilarity. In (C), the seven numbered clusters at height = 3.5 were most distinct based on indicator species analysis.

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native vines, with the most extensive coverage in aggregate obtained by the invasive English ivy (*Hedera helix*). Common species included Japanese honeysuckle (*Lonicera japonica*), porcelain berry (*Ampelopsis glandulosa* var. *brevipedunculata*), poison ivy (*Toxicodendron radicans*), multiflora rose (*Rosa multiflora*), Oriental bittersweet (*Celastrus orbiculatus*), Nepalese browntop (*Microstegium vimineum*), Virginia creeper (*Parthenocissus quinquefolia*), and reed canarygrass (*Phalaris arundinacea*) in addition to turfgrass. Hierarchical cluster analysis in Figure 5 indicated several compositionally distinct floras with little overlap (low degree of chaining) and others with less distinct compositions (high degree of chaining). Multivariate distance to centroid summaries indicated that no cluster was significantly ($p > 0.05$) more dispersed than others. Cluster 5EngIvy showed the broadest range of dispersion, with among the most and least dispersed examples. Seven relatively distinct groundcover clusters were summarized (see Appendix S1: Figure S6).

Over 50%, and in some cases approaching 75%, of all samples from clusters 1Porc, 2Poison, 4Lawn, 5EngIvy, 6Bitter, and 7JapHon fell within 50 m of woodland edges (see Appendix S1: Figure S7). Only cluster 3IvyGum showed a median distance >50 m from edges. Thus, in contrast to overstory samples, Baltimore's ground layers were overwhelmingly nonnative; variation among most types was largely determined by the abundance of a particular exotic, and most variation occurred within 50 m of a woodland edge. Interior spaces generally exhibited far less assemblage variation, particularly among light-requiring herbs and vines. Importantly, even when much of the ground flora was native, exotic vines like English ivy were typically present. These observations were corroborated by point-based indices.

Point-based indicators like Schumacher scores and penetrometer readings suggested widespread distribution of aggressive vines and relatively limited amounts of soil compaction (Table 1). The median of all Schumacher index scores exceeded 1.3, whereas 75% exceeded 0.5. Because the point-based Schumacher score is an average across all overstory stems at a point, it may be inferred that 75% of sampled points exhibited at least some vines on overstory stems. By contrast, because the upper quartile approached 3, over 25% of points had *average conditions* indicating vines had access to overstory canopies. Thus, English Ivy and other climbing vines were not only prevalent in the ground layer; they were also widespread on overstory stems.

Mean penetrometer readings per point showed a broad distribution, with median values approaching 827 kPa (120 psi) (Table 1). A value of 689 kPa (100 psi) typically indicates relatively limited soil compaction, so the fact that approximately 40% of values fell below this mark suggested most sampled soils were not very compacted. However, an upper quartile near 1379 kPa (200 psi) indicated that over 25% of points required 2–3 times the penetration pressure, an indication of severe compaction. Penetrometer readings may vary widely when collected on different days or under different antecedent conditions, so these distributions should be interpreted with caution, even as they provide useful context for understanding patterns among and within patches. One factor that may play a role in influencing penetrometer readings is the depth of organic horizons (Oa and A horizons). Across all samples, the interquartile range (IQR) spanned 1.5–11 cm with a median of 6.7 cm. Within this region, organic accumulations >4 cm are typically rare in natural soils, so such values may represent an agricultural history or the presence of exotic earthworms.

Crosspatch comparison

Because woodland patches are frequently units of interest for property owners and local neighborhoods, comparison and contrast among patches is often informative.

TABLE 1 Citywide distributions of parameters sampled from 845 distributed locations in 47 forest patches in Baltimore, Maryland.

Parameter	Units	*N*	Min	Max	Mean	Median	IQR
Overstory basal area	$m^2\ ha^{-1}$	47	3.06	39.02	16.17	16.07	9.9–21.4
Overstory richness	No.	845	1	11	3.67	4	2–5
Overstory H'	0–5	845	0	2.31	1.04	1.09	0.69–1.4
Overstory nativity	%	845	0	100	88.74	100	87.5–100
Schumacher index	0–5	845	0	5	1.73	1.4	0.5–2.86
Mean penetrometer	kPa	845	0	2758	899	827	345–1344
Groundcover	%	736	0	100	39.1	30	7–70
Groundcover richness	No.	736	0	13	4.1	4	3–5
Groundcover H'	0–5	736	0	2.33	0.95	1.01	0.61–1.36
Groundcover nativity	%	736	0	100	33	25	1.2–56

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As an example of the potential value of distributed data, we compared proportions of overstory clusters and summaries of percent organic matter (OM) within the upper 5 cm of soil across patches with >15 points to allow for inter-site summary (Appendix S1: Figure S9). Overstory cluster proportion provided an indication of predominant woodland types, and basal area estimates provided an index of aboveground carbon storage, whereas surface soil OM provided an indication of soil health and, indirectly, nutrient cycling, soil structure/water retention, biologic activity, and soil fertility/productivity. The soil metric showed within-patch OM variation that generally, but not always, tracked overall averages, and little correspondence to overstory basal area. However, using such comparisons, it was possible to understand how any specific site compared with others throughout the city.

Within-patch analysis

To illustrate the added value of distributed data, we assessed patterns of woodland attributes in relation to their spatial position within patches. An example of this analysis involved interpolation of various parameters across a single patch extent to detect regions of correspondence among attributes (Figure 6). Interpolation between points enabled visualization of potential correspondence as well as relationships with overstory cluster membership or digital terrain surfaces while situating these patterns relative to patch edges and interiors. In the patch shown in Figure 6, higher levels of overstory basal area showed some correspondence with soil bulk density, whereas there was a similar association among nonnative species, Schumacher scores, and percent soil organic matter. Nonnatives and vines were associated with recently disturbed canopies and moist woods within the patch, as drier sites in the south and southeast corner had higher levels of natives and hardwoods. When employed to assess multiple patches, such maps may prove useful for targeting removal efforts and conserving restoration dollars.

Analysis of univariate measures of woodland structure and composition (e.g., species richness) relative to canopy edges was accomplished using nCPA, where

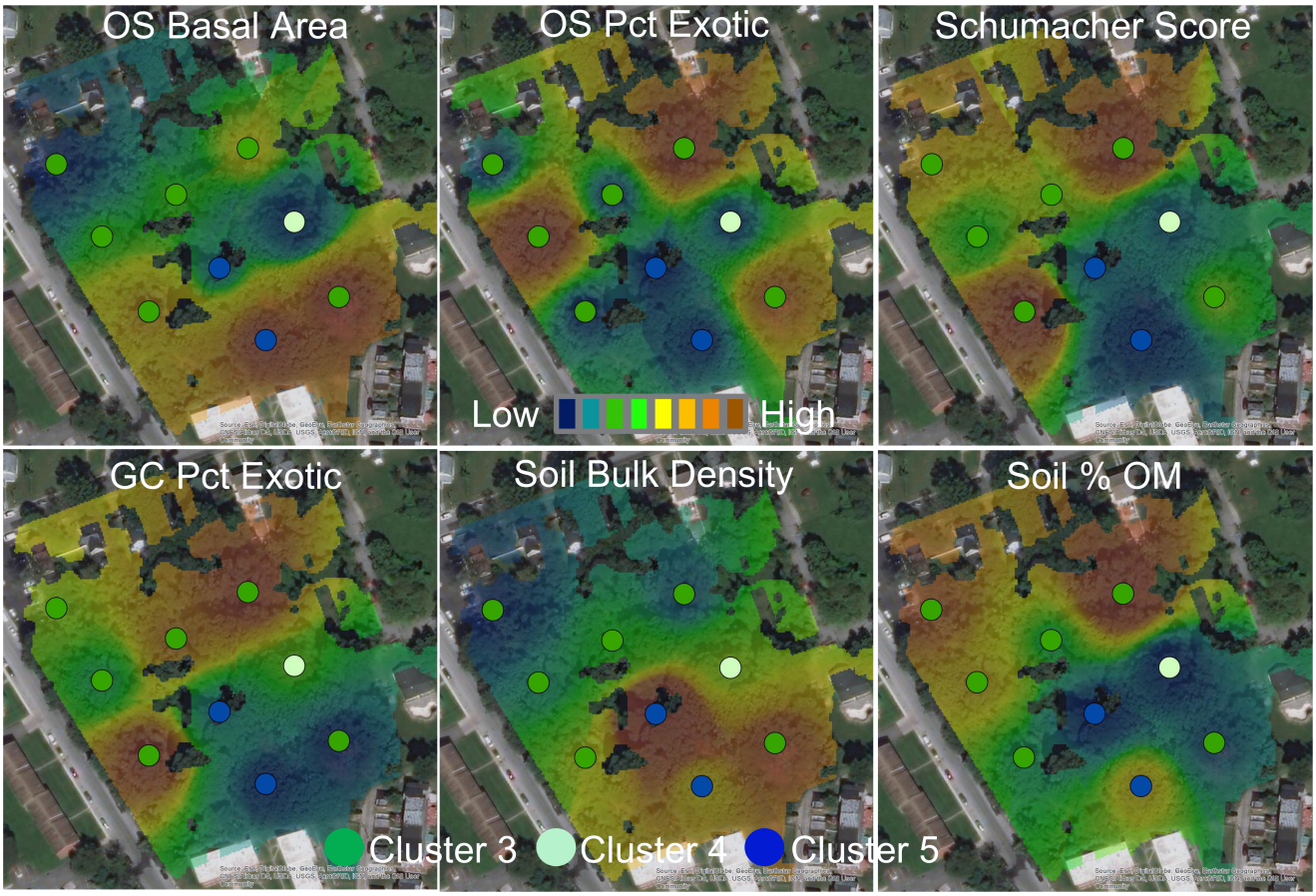

FIGURE 6 Inverse-distance-weighted interpolation of estimates of overstory basal area, percent exotic overstory stems, Schumacher vine encroachment index, percent exotic ground cover, soil bulk density, and percent organic matter from distributed point sampling within Springfield Woods, an urban forest patch in Baltimore, Maryland, USA, classified by overstory cluster type. *Source*: Imagery Google Earth. organic matter (OM).

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observed changepoints identified the magnitude and/or variance of each variable with the greatest difference along the distance gradient, as well as a 90% CI indicating uncertainty of changepoint location associated with different sample replicates (Table 2; Appendix S1: Figure S9). We were particularly interested in transitions signaling a departure from edge conditions as well as those consistent with woodland interiors, and so our focus included quantiles of bootstrapped changepoint replicates as well as observed values. For example, percent native overstory increased along edge-to-interior gradients. Although there were broad ranges of exotics along edges, the observed changepoint at 12.9 m suggested that woodland overstories became increasingly native toward woodland interiors. Groundcover samples showed a much higher nativity changepoint (51.4 m) with a narrower band of uncertainty that also appeared to trend toward greater nativity in deeper interior spaces.

Consistent with patterns of nativity, patterns of species richness, Shannon diversity, and overstory basal area increased from one side of the change point to the other along the edge-to-interior gradient (Table 2). Although a linear increase was not expected, increasing changepoints for overstory richness occurred at 17.6 m, Shannon diversity at 16.7 m, and basal area occurred at 47.9 m, whereas the changepoint for ground layer richness occurred at 15.6 m, Shannon diversity at 36.3 m, and same-day penetrometer readings at 25.2 m. Across vegetative changepoints in overstory and ground layers, we noted overlapping bands of uncertainty between 5 and 60 m. Although overstory basal area in woodland edges ranged from near 0 to 16 $m^2\ ha^{-1}$, the upper quartile of their distribution was lower than the median from woodland interiors. Similarly, species richness ranged from 1 to 11 in overstory samples and 0 to 13 in ground layers, but the distributions of both richness and diversity increased toward woodland interiors so that interior medians approached upper quartiles from edges (Table 2; Appendix S1: Figure S9). Finally, average penetrometer readings decreased toward woodland cores, even when measures were corrected for differences associated with different days or antecedent conditions.

With such structural variation, it was reasonable to explore compositional patterns relative to woodland edges. TITAN revealed changes in overstory and groundcover community composition along edge-to-interior gradients. Analysis of overstory data suggested that five tree species were distinctly associated with woodland edges, showing their greatest change in abundance and occurrence close to woodland margins (changepoint = 20.9 m, 90% CI = 13.2–37.9) with the greatest observed coincident declines from 15 to 20 m (Figure 7). This changepoint pattern remained consistent across bootstrap replicates, producing a definitive (leptokurtic) probability density at the community level despite a moderately low per-species z score (~3.3). Robust (declining) indicators of edge conditions included exotic species such as amur honeysuckle, tree-of-heaven (*Ailanthus altissima*), and white mulberry, as well as light-loving native pioneers such as black locust and boxelder (*Acer negundo*). By contrast, woodland interior species included 12 robust indicators (increasers) for a sum(z) of 84 (average z score per species ~7) that showed the greatest increase at 49.6 m (37.8–77). Most interior indicators were overstory dominants native to Maryland's woodlands, including northern red, white, and scarlet oaks (*Q. coccinea*), pignut hickory (*Carya glabra*), American beech, black gum, and tulip poplar. However, interior indicators also included phototropic natives like black cherry, along with sassafras (*Sassafras albidum*) and ash, that respond rapidly to canopy gaps. Interior indicators also displayed a broader range of species-specific changes along the edge-to-interior gradient than did edge indicators, contributing to multimodal uncertainty around community-level changepoints and indicating variability

TABLE 2 Nonparametric changepoints for parameters measured along a distance-to-edge gradient from 845 locations across 47 forest patches in Baltimore, Maryland.

Parameter	Units	*N*	changepoint (m)	90% CI	Mean < changepoint	Mean > changepoint	*p*
Overstory basal area	$m^2\ ha^{-1}$	845	47.9	7.3–55.2	15.05	20.64	0.001
Overstory richness	No.	845	17.6	7.6–214.7	3.3	3.9	0.002
Overstory H'	0–5	845	16.7	11.5–313.5	0.95	1.09	0.016
Overstory nativity	%	845	12.9	0.23–40.9	78	91.3	0.001
Mean penetrometer	kPa	845	174	112–1283.1	1026	835.6	0.011
Groundcover	%	736	100.4	0.6–239.2	39.9	33.4	0.441
Groundcover richness	No.	736	15.6	3.1–69.8	3.5	4.3	0.001
Groundcover H'	0–5	736	36.3	29.5–115.6	0.91	1.08	0.006
Groundcover nativity	%	736	51.4	29.1–58.2	28.2	43.1	0.001

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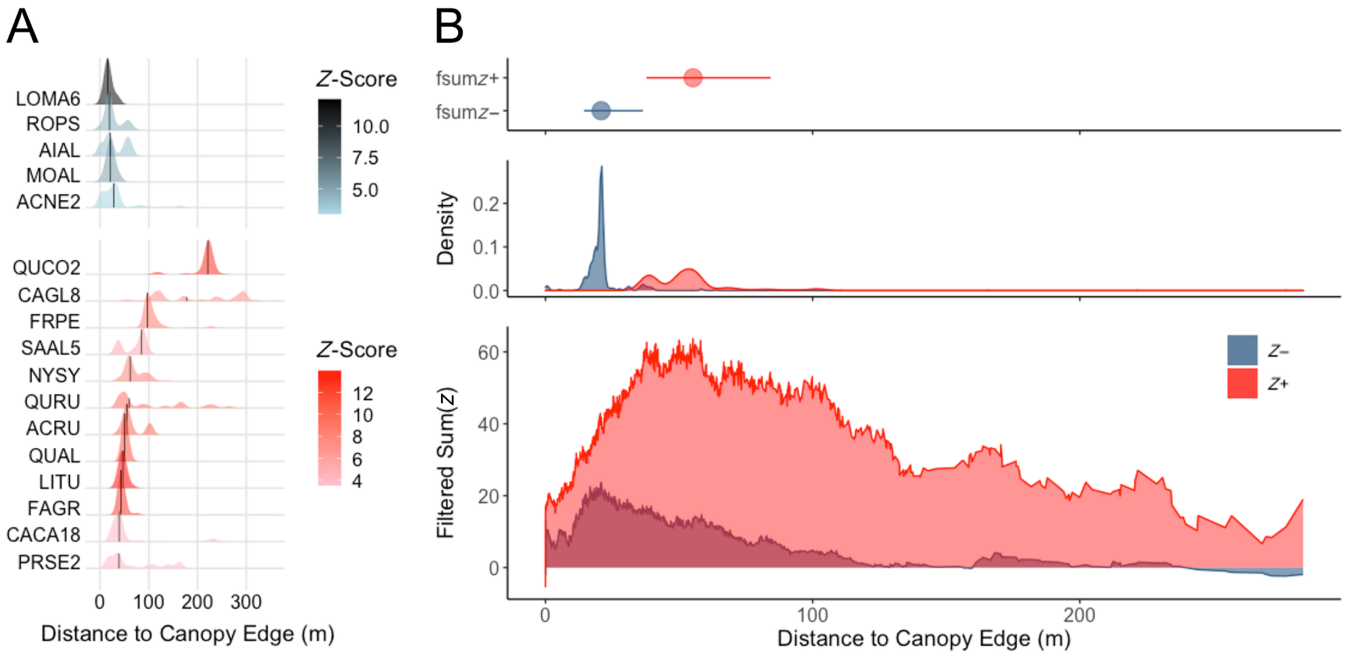

FIGURE 7 Results from Threshold Indicator Taxa Analysis (TITAN) on overstory community composition for 845 prism points along an environmental gradient defined by distance to canopy edge in Baltimore, Maryland, USA. (A) Changepoint distributions from 500 bootstrap replicates for pure and reliable indicators of edge conditions in blue, and interior indicators in red, with shading emphasizing change magnitude for each species. Decliners included amur honeysuckle (LOMA6), black locust (ROPS), tree-of-heaven (AIAL), white mulberry (MOAL), and boxelder (ACNE2), whereas increasers included scarlet oak (QUCO2), pignut hickory (CAGL8), green ash (FRPE), sassafras (SAAL5), black gum (NYSY), red oak (QURU), red maple (ACRU), white oak (QUAL), tulip poplar (LITU), American beech (FAGR), musclewood (CACA18), and black cherry (PRSE2). (b) The sum of z scores across both declining and increasing groups across the environmental gradient, the probability density of sum(z) maxima, and community changepoints along with their 90% CIs.

in response to interior gradients concentrated at the lower end of the CI.

Contrasts between edge and interior species were more pronounced within groundcover. Of the 12 species identified by TITAN, most experienced declines at distances <30 m, leading to a sum(z) >84 and an average per-species z score of ~7 (Figure 8). Once again, the greatest declines were immediate along canopy edges and near woodland margins (changepoint = 0.022 m, CI = 0.0–22.2). Indicators included graminoids such as oat (*Avena* sp.), nodding fescue (*Festuca subverticillata*), reed canarygrass, and other turf grasses, as well as common associates like white clover, plantago, and cinquefoil. In addition, annuals such as mugwort (*Artemisia vulgaris*), Canada goldenrod (*Solidago altissima*) and perennials such as ground ivy (*Glechoma hederacea*), porcelain berry, and amur honeysuckle showed strong affinity for edges.

Despite 12 interior groundcover indicators, the maximum sum(z+) remained <30, suggesting a relatively weak per-species signal of <2.5 z scores. TITAN identified a variable range of multimodal changepoints (Figure 8). As a result, the probability density for the observed changepoint of 109 m (40–194 m) was distributed broadly across the edge-to-interior gradient, indicating no clear zone of assemblage change. Among notable interior indicators were several native trees that might normally be found in forest ground layers (e.g., ash, tulip poplar, red maple, black gum) as well as herbs such as smooth Solomon's seal (*Polygonatum biflorum*) and Jack-in-the-pulpit (*Arisaema triphyllum*). In addition to the introduced herb common periwinkle (*Vinca minor*), there were also several shade intolerant vines found away from woodland edges (e.g., riverbank grape, virginia creeper, poison ivy, Oriental Bittersweet, and climbing nightshade, *Solanum dulcamara*). These species may well represent dispersal to interior canopy gaps such as streamside riparian zones or an ability to creep along forest floors in search of more favorable conditions. Regardless, most interior groundcover indicators did not increase until edge indicators had declined (i.e., >36 m).

From patterns of woody and herbaceous vegetation composition and structure along edge-to-interior gradients reflected in nCPA and TITAN, the maximum probability density of all changepoint replicates was 18.7 m, whereas the maximum probability density for groundcover was 15.2 m. Both vegetation types exhibited secondary peaks in cumulative probability densities at

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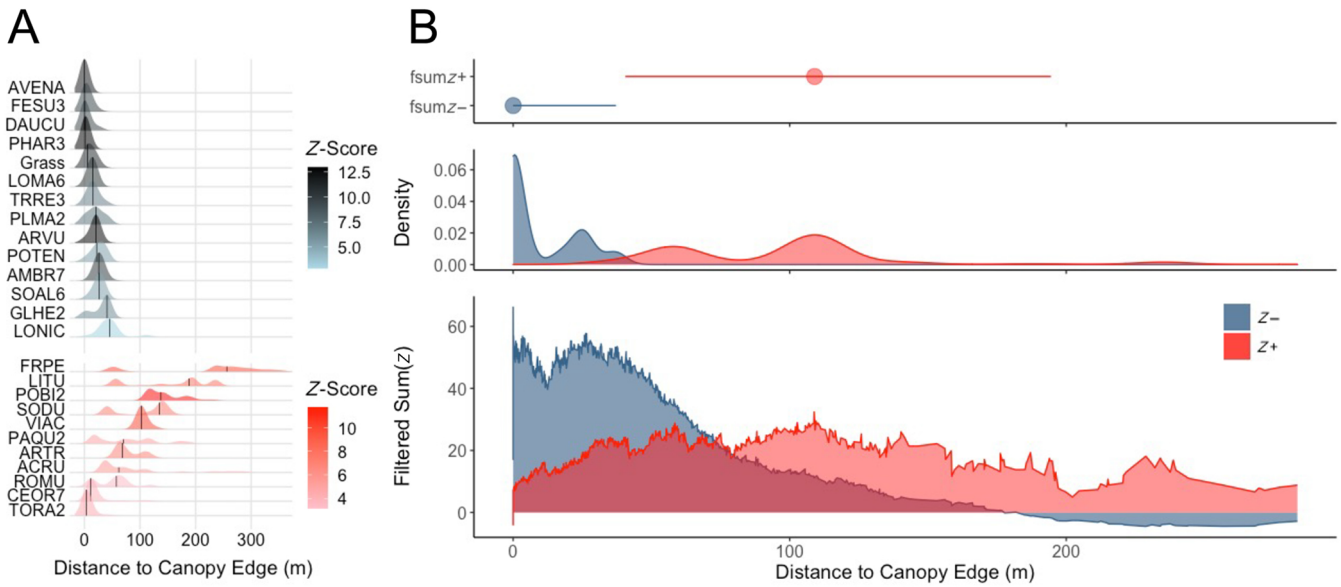

FIGURE 8 Results from threshold indicator taxa analysis (TITAN) on groundcover community composition from 763 1-m^2 quadrats along an environmental gradient defined by distance to canopy edge in Baltimore, Maryland, USA. (A) Changepoint distributions from 500 bootstrap replicates for pure and reliable indicators of edge conditions in blue, and interior indicators in red, with shading emphasizing change magnitude for each species. Decliners included oat (AVENA), nodding fescue (FESU3) reed canarygrass (PHAR3), turf grass (Grass), amur honeysuckle (LOMA6), white clover (TRRE3), common plantain (PLMA2), common wormwood (ARVU), cinquefoil (POTEN), porcelain berry (AMBR7), Canada goldenrod (SOAL6), and ground ivy (GLHE2), whereas increasers included green ash (FRPE), tulip poplar (LITU), smooth Solomon's seal (POBI2), climbing nightshade (SODU), maple-leaved viburnum (VIAC), Virginia creeper (PAQU2), common periwinkle (VIMI2), Jack-in-the-pulpit (ARTR), red maple (ACRU), black gum (NYSY), Oriental bittersweet (CEOR7), and poison ivy (TORA2). (B) The sum of z scores across both declining and increasing groups across the environmental gradient, the probability density of sum(z) maxima, and community changepoints along with their 90% CIs.

41.5 and 41.3 m, respectively. Cumulative probability density maxima were interpreted as estimates of the extent of the most abrupt edge effects in vegetation composition and structure across Baltimore's urban forest patches, with secondary peaks indicating transitions to interior forest conditions. In addition to informing subsequent analysis (see below), such characterizations have the potential to guide woodland mapping throughout the city.

Values of edge and interior changepoints were used as class breaks in evaluating the accumulation of species richness across various life forms (Figure 9). Rarefaction curves for herbs reached maxima of more than 65 species for both edge and interior samples, whereas transitional samples between edges and interiors were conspicuously depauperate, departing from other zones after only 20 samples and reaching a maximum of 40 species. Similarly, vine richness achieved a maximum of 18 species for edge and interior spaces, whereas transitional samples achieved a maximum richness of 14 species. By contrast, the rate of species accumulation was somewhat reversed for trees and shrubs. Both edges and transitional samples accrued species rapidly, yet it was clear that interiors achieved higher levels of richness. Fifteen shrubs were identified after fewer than 50 samples for edge and transitional samples, yet interiors continued to accumulate up to 20 shrub species. Approximately 50 samples also distinguished the richness among overstory trees in interior spaces from those in both edges and transitional samples. Overall, the rarefaction patterns suggest distinct patterns of biodiversity for each life form along edge–interior gradients.

DISCUSSION

As global urbanization continues to expand, more than 68% of the global population is expected to live in or around urban areas by 2050 (United Nations, 2018). Urban woodlands are characterized by high levels of fragmentation and disturbance that pose unique challenges for municipal land managers or other urban land stewards confronted with limited resources. This paper presents a method for rapid, cost-effective characterization of urban woodlands for a variety of purposes. It highlights the potential for agencies or organizations operating across different spatial extents to acquire and analyze data from individual forest patches and over broader metropolitan areas. The latter application will require due

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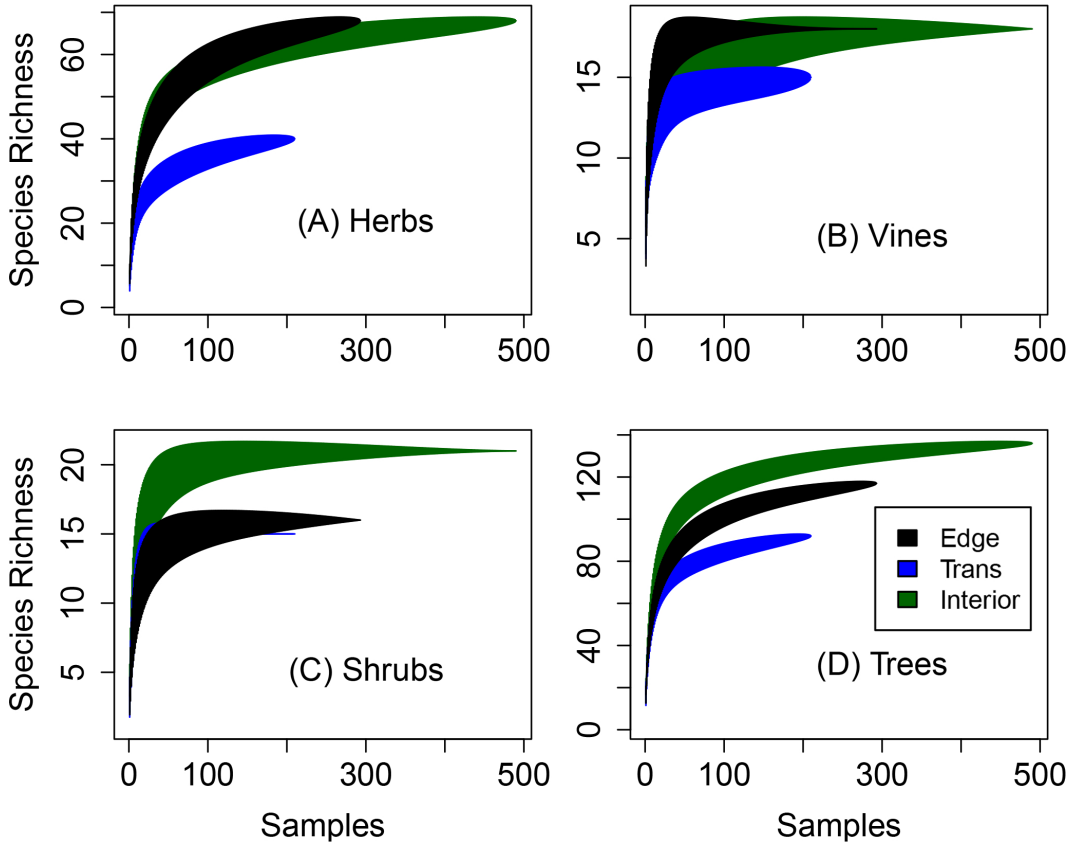

FIGURE 9 Species accumulation curves from rarefaction analysis across edge (<18.7 m), transitional, and interior (>41.5 m) for 845 samples of urban forest patches within Baltimore, Maryland, USA.

consideration of sampling design to ensure that points are representative of natural and anthropogenic gradients (Nowak, 2020). Although much urban sampling is performed at the plot scale and extrapolated across metropolitan areas, arguably the most relevant spatial unit for management is the forest patch, encompassing one or a small number of parcels. Data gathered using our methodology allow comparisons with forest patches, among patches, and along biotic or abiotic gradients (e.g., distance to forest edge) designed to provide actionable information and guide sound decision-making.

Simple summaries of the extensive data collection enabled by our approach characterized Baltimore's urban forest overstory as overwhelmingly native, though dominated by a range of successional conditions. By contrast, we found that ground layer vegetation was predominantly exotic, with the top ten most abundant species either actively invasive or ruderal native species that benefit from the predominance of disturbed canopy conditions. Recent characterization of forest patches in New York City documented similar patterns in overstory and understory vegetation (Pregitzer, Charlop-Powers, et al., 2019), despite overwhelming public ownership of woodlands (Morzillo et al., 2022), and similar patterns have been described in Philadelphia, Pennsylvania, and Newark, Delaware (Trammell et al., 2020). Moreover, we found that the median value of our vine encroachment score indicated that aggressive vines were widespread and thriving well into the interior of many patches, a finding that would be difficult, if not impossible, to document with conventional plot sampling. Finally, consistent with previous work (e.g., Phillips et al., 2019), we found that, despite symptoms of prior disturbance, most woodland soils lacked the compaction commonly associated with urban systems. The surface soils of our sites had bulk densities (1.15 ± 0.016 g cm^{-3}) comparable with forest patches sampled throughout the city (1.1 ± 0.037 g cm^{-3}) in a previous study (Pouyat et al., 2007), which were lower than other land uses including commercial and transportation, residential, and institutional. Because geology, historical patterns of agricultural land use, exotic introductions, or other environmental legacies may contribute to variation in OM content, other soil properties, as well as overstory composition, their interpretation merits scrutiny. Nonetheless, descriptive characterizations such as these may be useful for helping managers and residents understand the context of local management actions.

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Cluster analysis and ordination of prism point composition revealed at least seven types of overstory assemblages, highlighting potential drivers of Baltimore's woodland biodiversity. Although overstory clusters were initially distinguished largely based on plant associations with soil moisture and successional stage, a primary signal from widespread sampling was a high level of among-sample species turnover within three of the seven clusters (1ElmAmur, 2Locust and 5MapleGum). The degree of internal dissimilarity within these clusters meant that the composition of subdominant species was highly variable (as opposed to the comparatively uniform composition of mesic forests where only a few competitive species persist) and likely represented the impact of, and response to, anthropogenic disturbance. High levels of among-sample turnover in highly managed urban land uses can dramatically increase regional diversity (Swan et al., 2017). However, another plausible explanation is that clusters 1ElmAmur, 2Locust, and 5MapleGum also represent a combination of highly modified overstories with patterns of relative dominance reorganized from long-lived assemblages in clusters 3MesicOak, 4DryOak, 6BeechT, or riparian zones colonized following channel incision (Groffman et al., 2003). Such associations are characteristic of the region (e.g., Braun, 1951; Brush et al., 1980), and their edges can be expected to contain many species similar to woodland interiors. Moreover, although tulip poplar is a fast-growing pioneer of disturbed mesic sites (e.g., cluster 7TulipOak), it is reasonably long-lived and may yet dominate stands established in the latter half of the 20th century. This was apparent in our sample: inherent differences in both physical conditions and dispersal limitation along patch edges could reduce the predominance of long-lived overstory species, allow greater representation by early successional opportunists, and increase interpoint turnover. Distributed sampling allowed us to perceive both clusters 1ElmAMur, 2Locust, and 5MapleGum and their association with woodland edges or streamside riparian zones in ways that would likely be impossible with the randomization common in conventional plot-based sampling.

Our analysis suggested ground layers within Baltimore's woodlands were mostly nonnative, dominated by widespread exotic or light-requiring vines and aggressive (often bird-dispersed) shrubs. This result was consistent with what has been observed in more intensive plot sampling in urban forest patches of the eastern United States (Pregitzer, Ashton, et al., 2019; Pregitzer, Charlop-Powers, et al., 2019; Trammell et al., 2020), underscoring the effectiveness of rapid assessments for capturing general patterns. There was less structure within ground layers than overstory clusters due to high levels of compositional uniformity (i.e., a few ubiquitous species) combined with high among-group turnover (i.e., remaining species could have almost no overlap among samples) that limited robust ordination and useful clustering solutions. However, spatial patterns were nonetheless evident along edge-to-interior gradients, with distributed samples revealing clusters explicitly associated with woodland edges and those (i.e., 5IvyGum) with interior spaces more likely representative of native assemblages. By contrast, there were 12 ground layer species identified as robust indicators of interior conditions, and like patterns of overstory trees, none of these showed a very strong signal or coincident changes in space, suggesting their distribution was not strongly determined by edge proximity. Thus, our approach not only highlighted the threat of exotic predominance in ground layers but also its association with edge habitats.

Overall, clustering allowed for the classification of woodlands at the scale of individual patches and their subcomponent stands. Distributed soil measurements were also useful for interpreting woodland composition within patches and may also be useful in associating specific patches with their land use/management history (Sonti et al., 2024). For example, interpolating distributed samples can help detect associations between surface soil organic content and bulk density, or whether OS basal area is associated with either lower Schumacher scores or exotic proportions. Many forest patches, from overstory canopy to underlying soils, were less degraded than is often assumed, with great potential to provide ecosystem services and functional revitalization (e.g., water storage capacity for stormwater management and/or carbon sequestration). However, there were also important differences among individual patches and the distribution of well-organized or disturbed woodlands that were relevant for land management. Many patches were threatened by aggressive vines and exotic species that may shorten both the longevity and reproductive success of extant overstory canopy while altering soil nutrient availability (Matthews et al., 2016; Ward et al., 2020). Such impacts may compound conventional disturbances such as fire exclusion, metabolic acceleration, and deer browsing (Johnson et al., 2020; Sonti et al., 2019; Templeton et al., 2019). Managers and municipalities focused on climate resilience could target conservation and restoration efforts around specific cluster types to focus on conserving extant woodlands and sustaining native assemblages in forest regrowth.

Perhaps most notably, distributed sampling allowed for evaluation of diversity in unprecedented detail along edge-to-interior gradients, both among and within specific urban forest patches. Early data exploration made it clear that internal gaps from downed trees and/or streams could have important impacts on species

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distributions, just as gradients relative to woodland margins. Such internal gradients were simply not apparent from aerial views and would likely be missed using conventional plot-based sampling, even if multiple plots were employed within a single patch. Analysis along edge-to-interior gradients using nCPA revealed shifts in patterns of exotic invasion in both overstory and groundcover samples, overstory basal area, and richness. Such structural shifts are to be expected, as edge habitats are thought to be sites of more frequent disturbance, lower soil organic content, and distinct microclimates, as well as being more open to colonization by exotics (Bae & Ryu, 2021; Bergès et al., 2013; Li et al., 2018; Matlack, 1993; Pregitzer, Ashton, et al., 2019; Pregitzer, Charlop-Powers, et al., 2019; Trammell et al., 2020). However, what was perhaps more unexpected was the congruence of all results, derived from multiple metrics and hundreds of bootstrap replicates, pointing toward more discrete edge effects than previously described for urban landscapes or that were likely to be exposed by univariate analysis.

TITAN revealed clear compositional shifts along edge-to-interior gradients for both overstory and groundcover assemblages. Aggregate results provided a high degree of spatial detail, documenting edge effects, zones of uncertainty around overall changepoints, and characterizing community changes along woodland edges. A rather unique aspect of TITAN results was the ability to understand contributions of individual species to patterns of community change, even if not every species responded precipitously to the environmental gradient (Baker & King, 2010, 2013). Results from TITAN also corroborated those from other compositional and structural measures, suggesting distinct zones delineating edge (<18.7 m), transitional, and interior conditions (>41 m) that exhibited distinct patterns of biodiversity.

Rapid, low-cost sampling with standardized information collection protocols enabled comparison across multiple scales, encouraging repeated sampling and adaptive management responses to changing forest conditions. The protocol is "rapid" compared with areal plot sampling of 200–300 m^2 due largely to the time saved in laying out plot boundaries, measuring overstory stem diameters, and assessing both understory and ground cover. In our experience, a team of two or three interns familiar with the protocol could complete a single point sample in between 15 and 30 min versus several hours with areal plots. Thus, depending on its size, systematic, spatially extensive sampling of a forest patch can be accomplished within a day or two, in most cases. A key constraint on the collection of such data is the level of professional training required for field personnel. Our protocol does require plant identification skills and some instrument training, but the tree measurements required are simpler and fewer than those of plot-based urban forest protocols such as i-Tree Eco (Nowak, 2020) and are replaced with greater information regarding groundcover composition and soil characteristics. Although surface soils do not always reflect deeper soil profiles, we used representative auger samples to contextualize and identify anomalies within surface collections. Even so, our understanding of the contribution of deeper soil dynamics to ecosystem services was necessarily limited.

One conspicuous loss from this type of prism sampling is the absence, beyond seedlings in the ground layer, of demographic information inherent in size class distributions and the ability to analyze overstory recruitment. This information could feasibly be obtained with marginal additional effort by adding stem counts within a small radius (e.g., 2–4 m) of every prism point at the cost of additional time at each point. In addition, if stem density estimates are needed for biomass estimation over broader extents, noting the size class of prism stems may fulfill that need (with associated error), as would employing quarter-point sampling at each point. Information obtained from distributed sampling is arguably more effective than areal plots in landscapes or patches with variable size classes and is directly applicable to typical management actions (e.g., invasive removal, edge management, planting, soil amendments, biomass estimates). Further, over larger patches with greater interior uniformity or in more rural contexts, it is possible to modify collection density (e.g., every 80 m) to reduce overall sampling effort and yet still achieve adequately distributed characterization of within-patch gradients. Key criteria would depend on the goals of the sampling effort and the anticipated application of the resulting information.

Distributed sampling allows for explicit estimates of biomass using prism stem counts, when combined with some information regarding stem density distributions (e.g., from a representative areal plot), as well as spatially explicit information that can be used to direct management decisions. For example, recent restoration budgets for Springfield Woods (depicted in Figure 6) were substantially reduced once it was recognized that intensive invasive removal would only be needed for about 60% of the patch area (BGS, 2020). Thus, the information obtained from distributed sampling altered both the restoration budget and the location of targeted effort. Furthermore, widespread adoption of similar methodologies could allow for common data collection across multiple urban areas, enable cross-city comparisons, and encourage information sharing to address generalizable practices and problems (e.g., Pregitzer, Plitt, et al., 2020).

Because many cities typically do not consider, or do not have access to, information regarding the relative

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nativity, ecological value, or uniqueness of specific natural areas in conservation and management decisions (e.g., Huff et al., 2020), these and similar data could also be used to build awareness and support advocacy for the conservation and restoration of forest patches. A local example is the nonprofit organization, Baltimore Green Space, which has used the data described here to begin to quantify the ecological structure of urban woodlands and advocate for the modification of forest conservation laws by Baltimore's City Council. As part of efforts to broaden the property tax base, current policy allows for resident owners within the city to purchase adjacent, vacant, and municipally owned parcels from the city at substantial discounts (Morzillo et al., 2022). As residents acquire new land, it is often cleared to expand lawns or add new buildings, further fragmenting extant canopy. Our data suggest that such fragmentation can degrade Baltimore's woodlands by converting interior spaces to edges, removing native overstories without consideration for their conservation value, encouraging colonization by early successional species, exotics or aggressive vines, as well as exposing sites to potential soil compaction. The impacts of such policies are solely related to the minimum area of urban forest under the forest management conservation statute, which was recently reduced from 1858 m^2 (20,000 ft^2) to 464.5 m^2 (5000 ft^2) in response to collective advocacy. Such policy change may help to disincentivize forest patch clearing and reduce ongoing rates of fragmentation within the city, especially when bolstered with evidence supporting the need for regional control of invasive species.

Overall, within the United States and elsewhere, there is a pressing need to characterize urban woodlands across many cities that lack the resources to support widespread and intensive forest sampling (Pregitzer, Charlop-Powers, et al., 2020; Pregitzer, Plitt, et al., 2020). In most cases, such limited sampling may not provide cities with the rapid, actionable information needed to support management and policy decisions. We have proposed a relatively rapid and cost-effective protocol for characterizing urban woodlands that provides utility over metropolitan areas while allowing for comparison both among and within forest patches. We have used quantitative and qualitative analysis, as well as specific examples, to illustrate the generic utility of our protocol for a range of applications, as well as its ability to produce new insight that leads to management action and informed conservation planning.

AUTHOR CONTRIBUTIONS

Matthew Baker helped develop the protocol, advised data management, conceived of the paper, supervised all data analyses, was the primary author and editor. Ian Yesilonis helped develop the protocol, analyzed soil samples, contributed to paper conception, and contributed to writing and editing. Laura Templeton helped collect and manage data, supervised field crews, and contributed to editing. Beatriz Shobe helped collect and manage data, supervised field crews, and contributed to editing. Jaelyn Bos helped manage and merge data, performed initial data analyses, and contributed to editing. Nancy F. Sonti reviewed the protocol and analyses, contributed to paper conception, and contributed to writing and editing. Katherine Lautar helped develop the protocol, supervised data management, conceived of the paper, and contributed to writing and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data (Baker et al., 2025) are available from the Environmental Data Initiative (EDI) Data Portal: https://doi.org/10.6073/pasta/1c5c63320541b9a65da3a94df04c80f4.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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