



Shaping Baltimore's urban forests: past insights for present-day ecology

Nancy F. Sonti · Matthew E. Baker ·
John J. Lagrosa IV · Michael Allman ·
J. Morgan Grove · Michelle P. Katoski

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Abstract

Context Land use history of urban forests impacts present-day soil structure, vegetation, and ecosystem function, yet is rarely documented in a way accessible to planners and land managers.

Objectives To (1) summarize historical land cover of present-day forest patches in Baltimore, MD, USA across land ownership categories and (2) determine whether social-ecological characteristics vary by historical land cover trajectory.

Methods Using land cover classification derived from 1927 and 1953 aerial imagery, we summarized present-day forest cover by three land cover sequence classes: (1) Persistent forest that has remained forested since 1927, (2) Successional forest previously cleared for non-forest vegetation (including agriculture) that has since reforested, or (3) Converted forest that has regrown on previously developed areas. We then assessed present-day ownership and average canopy height of forest patches by land cover sequence class.

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N. F. Sonti (✉) · J. M. Grove
Northern Research Station, Baltimore, USA
e-mail: nancy.f.sonti@usda.gov

M. E. Baker · J. J. Lagrosa IV · M. Allman · M. P. Katoski
University of Maryland, Baltimore County, Baltimore,
USA

Results More than half of Baltimore City's forest has persisted since at least 1927, 72% since 1953. About 30% has succeeded from non-forest vegetation during the past century, while 15% has reverted from previous development. A large proportion of forest converted from previous development is currently privately owned, whereas persistent and successional forest are more likely municipally-owned. Successional forest occurred on larger average parcels with the fewest number of distinct property owners per patch. Average tree canopy height was significantly greater in patches of persistent forest (mean = 18.1 m) compared to canopy height in successional and converted forest patches (16.6 m and 16.9 m, respectively).

Conclusions Historical context is often absent from urban landscape ecology but provides information that can inform management approaches and conservation priorities with limited resources for sustaining urban natural resources. Using historical landscape analysis, urban forest patches could be further prioritized for protection by their age class and associated ecosystem characteristics.

Keywords Urban ecology · Historical aerial imagery · Land cover change · Urban environmental history · Urban forested natural areas

Introduction

Land use history of secondary forest across the eastern United States impacts species composition and ecosystem function (Foster et al. 1998; Bellemare et al. 2002; Hooker and Compton 2003). This is true in urban areas as well as rural areas, yet the history of urban forested natural areas is rarely documented (but see Fahey and Casali 2017; Nix et al. 2022; Pregitzer et al. 2023). The importance of urban natural areas is increasingly recognized, for social and biophysical ecosystem services as well as resilience of urban systems (Threlfall and Kendal 2018; Johnson et al. 2021). These critical natural resources exist across a spectrum of land uses encompassing formal and informal site types from protected lands to vacant lots (Threlfall and Kendal 2018; Morzillo et al. 2022). A better understanding of urban woodland site history can reveal the ways in which the distribution of so-called “natural” landscapes are the result of complex social histories (Ogden et al. 2018). This information can be used to inform and prioritize present-day conservation and management efforts across public and private lands.

Forests in cities can vary widely in species composition, structure, successional state, and level of invasion by non-native understory plant species (Pregitzer et al. 2019a; Baker et al. 2024). This heterogeneity reflects, in part, the diversity of site histories underlying present-day urban forests. Legacies of soil disturbance, disrupted hydrology, and altered seed banks from previous agricultural or urban land uses may impact soil quality, vegetation growth and expected successional trajectories (Bossuyt and Hermy 2001; Dupouey et al. 2002; Flinn and Vellend 2005; Kaye et al. 2006; Alfaro-Sánchez et al. 2019). Recent work from the Chicago, Illinois region found that older remnant forests had higher canopy cover, basal area, and native species dominance than recently established forests (Fahey and Casali 2017). Similarly, Pregitzer et al. (2023) found that forested sites in New York, NY with more recent histories of agriculture, lawn, or built environment had lower basal area and higher amounts of invasive plant species groundcover. However, little is known about how urban forest site histories and related structural characteristics vary with land ownership, parcel size, or other social factors.

Within the emerging field of historical urban landscape ecology, historical aerial imagery has been used to examine tree canopy or forest change at different spatial and temporal scales. Recent studies have investigated change in urban tree canopy cover of Philadelphia, Pennsylvania, delineating patches of canopy cover within targeted study areas and linking these changes to historical management practices. Increases in canopy cover during the late twentieth century and early twenty-first century on the campus of the University of Pennsylvania were attributed to intentional planning and design decisions, with long-term support for tree planting and maintenance (Roman et al. 2017). Tree canopy gains during the 1960s and 1970s in three large Philadelphia parks were attributed to both purposeful tree planting and reforestation activities and to unintended forest expansion associated with municipal budget cuts and reduced mowing (Nix et al. 2022). Tree canopy cover delineated across two mid-size post-industrial Massachusetts cities found canopy gains during depressed economic periods and canopy losses during strong economic periods from 1952 to 2014 (Healy et al. 2022). Point-based land cover interpreted from 1970 to 2010 aerial imagery has been used to link urban land cover changes with sociodemographic changes across Philadelphia neighborhoods (Locke et al. 2023). This work finds that tree canopy is more persistent in protected open spaces compared to developed lands, and that increases in tree canopy were due to processes of urban renewal, greening initiatives, low-density housing development, and the previously mentioned forest expansion due to lack of maintenance (Roman et al. 2021).

Previous studies have documented forest fragmentation and land use conversion across a gradient of urbanization in the Gwynns Falls watershed region of Baltimore, Maryland over sub-decadal (Zipperer et al. 2012) and century (Zhou et al. 2011) timescales. Zhou et al. (2011) found that while total forest area in the Gwynns Falls watershed remained constant from 1914 to 2014, the forest cover became increasingly fragmented and less than 20% of the initial forested area persisted through this time period. In addition, the location of high rates of forest cover change shifted from urban to suburban bands over time, coinciding with the shift of development activities across the landscape. Similarly, an assessment of forest cover in the Chicago, Illinois region over two

centuries found that increased urbanization resulted in greater forest fragmentation but not greater overall conversion (Fahey and Casali 2017). These studies document dynamics of tree canopy or forest conversion and expansion across urban regions, and their likely causes. However, in order to conserve and manage present-day urban forested natural areas across the various land ownerships that make up a city, there is a need to better understand the distribution of historical land use and land cover trajectories across this critical natural resource.

The objective of this study was to investigate the historical land cover trajectories of present-day forest cover across Baltimore, Maryland, USA. We used maps of land cover derived from 1927 and 1953 aerial imagery to characterize spatiotemporal changes in land cover across present-day forest patches mapped using high-resolution urban tree canopy cover data from 2018. Similar to other post-industrial cities, Baltimore experienced urban expansion over a rural landscape and subsequent economic decline during the past century. Local dynamics of development, abandonment, urban renewal, and infill resulted in a heterogeneous landscape of forest patch extent and condition. We examined differences in historical land cover change patterns across present-day public and private forest land ownership categories, as well as associated differences in average canopy height, average parcel size, and number of ownerships per forest patch. Landscape change patterns were assessed and then contextualized using representative case studies of focal areas in Baltimore City representing common land cover sequences.

Methods

Study area

Like many cities of the northeast and 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 (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 and 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, and Herring Run.

Following western European settlement during the seventeenth century, forests of the region experienced widespread clearing for agriculture and to supply fuel for foundries (Benitez and Fisher 2004; Zhou et al. 2011). Initially driven by tobacco exports, many farms were converted to corn or wheat rotations and nearly complete clearing was documented by the end of the eighteenth century. Migration to midwestern and western territories during the mid-nineteenth century and post-Civil War population shifts led to moderate secondary afforestation, and city planning led to parks along Herring Run, Perring Run, and Chinquapin Run as well as Leakin Park along the Gwynns Falls, and Cylburn Arboretum and Druid Hill Park along the Jones Falls.

In 1927, Baltimore was experiencing rapid change and growth. The city had been expanding from a colonial settlement to an economically prosperous urban and industrial center throughout the nineteenth century (Foresman et al. 1997). In the early twentieth century, Baltimore was seventh in the nation in population but sixteenth in land area, with a population density greater than New York City (Brooks et al. 1979). A fire burned 57 hectares of downtown in 1904, yet the city had rebuilt much of that area by 1927. In 1918, the city tripled in size by annexing an additional 160 km² of predominately agricultural and forested lands (Crenson 2019). Many manufacturing plants opened during the 1920s, and Baltimore rose from the seventh to third most active port in the nation (Crenson 2019). Large corporations built new skyscrapers downtown, but green space was still on the minds of Baltimore's planners. The Baltimore City Forestry Division had been established during the previous decade, and the first City Forester was hired to care for the city's trees, including reforestation of the City's reservoir watersheds (Buckley 2010). Although on the brink of the Great Depression, Baltimore's boosters predicted population growth past one million before the middle of the twentieth century (Crenson 2019). Baltimore City's population would in fact reach 805,000 by 1930 and increase for another two decades to 950,000 people in 1950 before starting to decline to a population of

586,000 as of 2020 (US Census 2021). Between 1960 and 2010 the population of the surrounding metro region increased by 60% while the City's population shrank nearly 34% (Irwin et al. 2019). Displacement of urban populations to surrounding suburbanizing lands after World War II exacerbated patterns of woodland clearing, further fragmenting forest remnants in proximity to residential development (Zhou et al. 2011). At the same time, depopulation and economic decline throughout the second half of the twentieth century led to a large number of vacant properties in the urban center (Boone et al. 2009). The city has over 18,000 vacant lots, many of which are green spaces or even forested (Kvit et al. 2022, Ogden et al. 2019).

Based on a recent land cover assessment derived from 2018 aerial imagery and lidar, 28.7% of Baltimore's total land area of 210 km² was covered by urban tree canopy with 22.9% of that tree canopy in forested areas (Chesapeake Bay Program 2023). Recent analyses show an increase in Baltimore's total tree canopy cover but a decrease in forest canopy cover during the past decade (Chesapeake Bay Program 2022). Today, forest patches exist across Baltimore's landscape on a variety of land uses and ownership regimes, and in varying social-ecological contexts (Ogden et al. 2018; Sonti 2019; Baker et al. 2024). State and municipal agencies and regulations seek to conserve existing forest cover on public and private lands (Baltimore Office of Sustainability 2023), and local organizations such as the non-profit Baltimore Green Space work to steward and protect Baltimore's forest patches from clearing and ecological degradation (Avins 2013).

Historical land cover mapping

Georectified mosaics of 1927 and 1953 aerial imagery were used for land use/land cover classification (Lagrosa et al. 2021a, 2022a). The 1927 dataset was created from 93 images captured between October 1926 and February 1927 by the Chesapeake Aircraft Company. The 1953 dataset was created from 113 images captured between August 1952 and February 1953 by the US Department of Agriculture. The extent of both mosaics includes all of present-day Baltimore City and portions of surrounding Baltimore County. In this paper, we only examined Baltimore City land cover.

Heads-up digitizing was performed in ArcGIS to create a land-use/land cover map for eight classes based on a modified Anderson Level II classification system (Anderson 1976; Lagrosa et al. 2021b, 2022b). Criteria for classification were interpreted by the GIS analyst and included identifying and dissolving areas within classes that did not meet the minimum mapping unit of 0.405 hectares (~1 acre). More details about the land-use/land cover classification methods can be found in Lagrosa et al. (2021b, 2022b). Land use can be difficult to determine from historical imagery. Thus, for the present analysis, eight land-use/land cover classes were collapsed to four broader land cover classes: forest, non-forest vegetation (includes agriculture and grass/shrubland classes), developed (includes residential/commercial, industrial, built – other, and barren classes) and water (Fig. 1).

Present-day forest patch delineation

A citywide urban tree canopy map based on a recent land cover assessment derived from 2018 aerial imagery and lidar (Chesapeake Bay Program 2022) was used to map Baltimore's forest patch canopy cover. First, "hard canopy" was distinguished from "soft canopy" using impervious surface cover taken directly from planimetric layers and building footprints accessed from the City of Baltimore, MD data repository (e.g., Alonzo et al. 2021). Hard canopy was determined by its overlap with impervious surfaces including rooftops, roads, and other paved surfaces. Forest patches were then delineated using morphological spatial pattern analysis (MSPA; Vogt et al. 2007) using an edge parameter of 15 m based on observed changes in vegetation composition and structure (Baker et al. 2024). MSPA applies the edge parameter to distinguish interiors (i.e. 'cores') from surrounding edges, as well as five other morphometric primitives (i.e., branches, bridges, loops, perforations, and islets) that reflect how canopy is or is not connected to cores. Forest patches included all core areas, their surrounding edges, as well as any perforations (internal edges around gaps). Other MSPA classes of tree canopy were eliminated as they were too small to contain core forest. Resulting patches were further distinguished into forested natural areas (FNAs) and groves. FNAs were required to have a minimum core thickness greater than 22.6 m, whereas groves have less substantial core area. Although groves

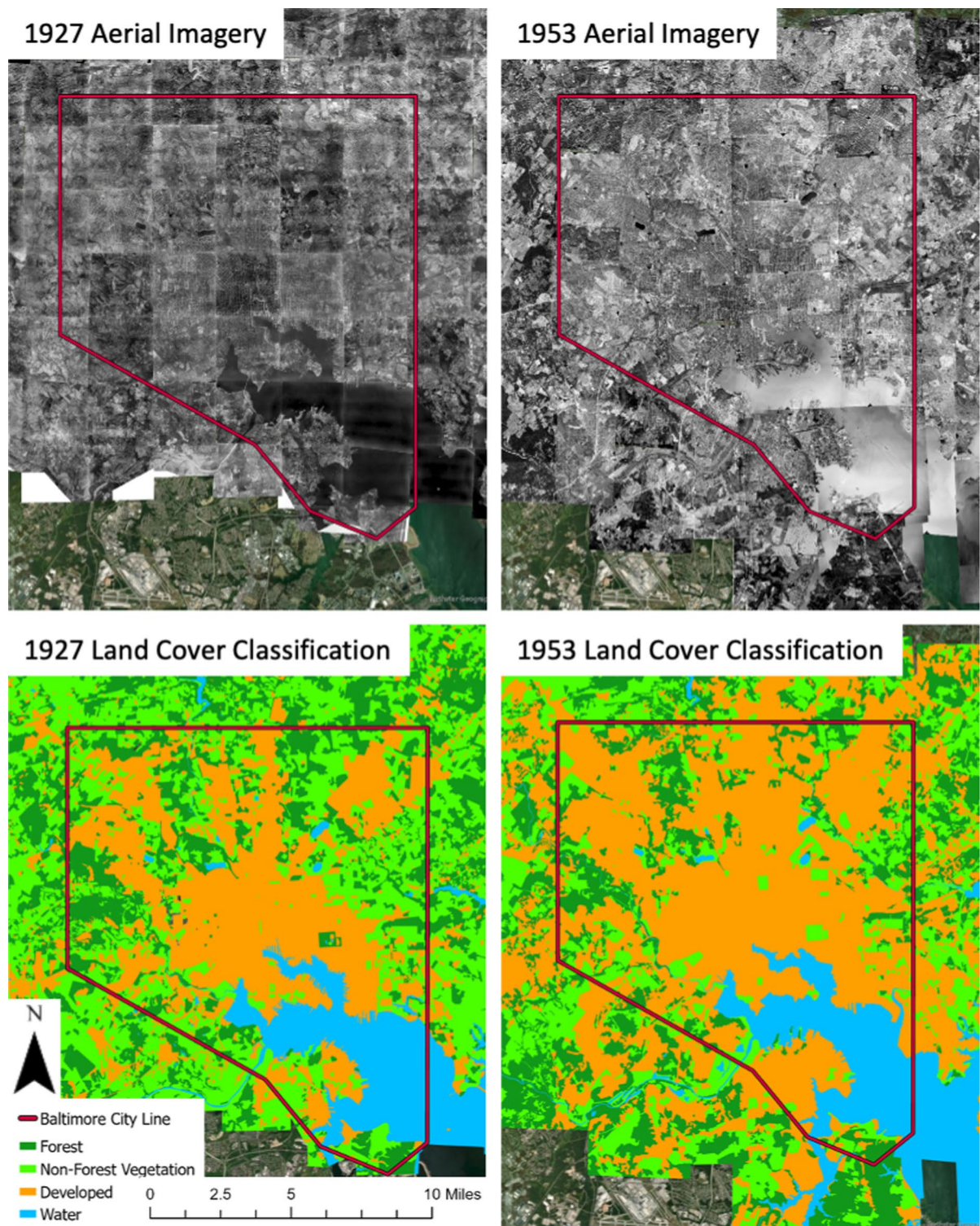


Fig. 1 Georectified aerial imagery and land use/land cover classification from 1927 and 1953 depicting Baltimore City and portions of surrounding Baltimore County

often have qualities of natural forested ecosystems (i.e., minimal understory management, decomposition, natural regeneration), we only include the larger FNAs in the present analysis due to their comparability to the historical land cover dataset (groves would be smaller than the minimum mapping unit of 0.405 ha used for the historical land cover classifications). Out of 406 FNAs mapped across Baltimore City, only 15 were less than 0.405 ha. These FNAs were partly or entirely forested in the historical land cover classifications. Hereafter, we refer to FNAs as “forest” or “forest cover”.

Data summaries and analysis

We assessed historical land cover of present-day forest cover both citywide and by present-day forest land ownership classes. In addition to reporting descriptive statistics, we used Sankey diagrams (Cuba 2015) to depict changes in categories over time. Segments of each forest patch with a unique land cover history were assigned to one of three sequence classes of ecological interest (Table 1): (1) Persistent Forest (Persistent) that has remained forested since 1927, (2) Vegetation Succession (Successional) that was previously cleared for non-forest vegetation (including agriculture) in 1927 and/or 1953 and has since reforested, or (3) Development Conversion (Converted) where forest has regrown on areas that were previously developed in 1927 and/or 1953. One-way Welch’s Analysis of Variance was used to compare socio-ecological characteristics of present-day forest patches (average total parcel size (including forested and non-forested area), number of unique property owners, average tree canopy height) by historical land cover sequence class (Persistent, Successional, Converted). To further examine spatial patterns in land cover change, a citywide map was created summarizing categories of land cover change among sequence classes (Fig. 2). Citywide patterns and local case study areas were examined and discussed.

Results

Historical land cover trajectories of Baltimore City’s present-day forest

More than half (54%) of Baltimore City’s present-day forest cover has been forested since at least 1927,

Table 1 Area (ha) and percent of present-day (2018) forested cover by historical (1927–1953) land cover sequence in Baltimore, MD

1927 → 1953 Land cover sequence preceding present-day forest cover	Area (ha)	Percent
Persistent forest		
Forest → Forest	774.01	54.6
Vegetation succession		
Non-forest veg → Forest	206.99	14.6
Non-forest veg → Non-forest veg	140.01	9.9
Forest → Non-forest veg	74.92	5.3
Development conversion		
Non-forest veg → Developed	60.87	4.3
Forest → Developed	55.57	3.9
Developed → Forest	42.77	3.0
Developed → Developed	28.25	2.0
Developed → Non-forest veg	15.21	1.1
Other		
Forest → Water	6.23	0.4
Non-forest veg → Water	4.89	0.3
Water → Forest	1.66	0.1
Developed → Water	1.76	0.1
Water → Water	0.71	0.1
Water → Non-forest veg	1.66	0.1
Water → Developed	1.91	0.1

and 72% since 1953 (Table 1, Fig. 2). About 30% of present-day forest has undergone natural succession from non-forest vegetation at some point during the past century, while 15% has reverted back to forest cover from some type of developed land cover during that time period. Across all categories of historical land cover change, the majority of present-day forest is found on municipal land owned by Baltimore City and a small amount is owned by state and federal government (Fig. 3, Supplemental Table S1). However, a greater proportion of forest that has been converted from previous development is currently under commercial/industrial or private residential ownership, while persistent and successional forest are more likely to be municipally-owned.

A Sankey diagram depicting the change in historical land cover from 1927 to 1953 further illustrates the shifts within categories of present-day forest ownership (Fig. 4). As the city expanded, the amount of present-day forest that remained non-forest vegetation decreased from 1927 to 1953 (413 to 232 ha), while the amount that was developed or forested increased

(88 to 147 ha and 910 to 1025 ha, respectively). A greater proportion of land shifted from non-forest cover to forest between 1953 and the present (392 ha) than from 1927 to 1953 (251 ha). However, there are certainly areas that went from non-forest in 1927 to forest in 1953 and have since reverted to non-forest that are not included in our analysis. There was also 128 ha that switched from forest in 1927 to non-forest vegetation in 1953 and back to forest by the present day. Areas of present-day forest that were converted from non-forest or forest cover in 1927 to developed land in 1953 were more likely to be under private (residential, commercial/industrial, or institutional) rather than public ownership. Within private ownership classes, institutional land was more likely to remain in forest or non-forest vegetation from 1927 to 1953, while present-day commercial and private residential forest was more likely to undergo land cover change between those time periods. Although the Sankey diagram effectively highlights that large proportions of present-day forested areas have experienced either no shifts or gradual afforestation over the past century, a substantial fraction dominated by private ownership appears much more dynamic. What the diagram does not show are the spatial patterns of that dynamic, as well as their scope and scale throughout the city.

Characteristics of present-day forest by land cover sequence class

The average size of Baltimore property parcels containing present-day forest cover is significantly different among all three historical land cover sequence classes ($F\text{-value}=23.17$, $df=2$, $p\text{-value}<0.0001$; Fig. 5). Forests that have undergone succession from non-forest vegetation during the last century were found on the largest parcels (median avg parcel size=8.8 ha), followed by persistent forest (5.3 ha), followed by forest on formerly developed land (2.3 ha). The number of distinct property owners in areas of successional forest cover is significantly different from that of persistent forest or forest converted from development ($F\text{-value}=12.44$, $df=2$, $p\text{-value}<0.0001$; Fig. 6). Persistent and converted forest patches have a median number of 2 property owners, while successional forest has a median of 1 property owner per forest patch. The average tree canopy height was significantly greater in patches of

persistent forest (mean=18.1 m) compared to tree canopy height in successional and converted forest patches (16.6 m and 16.9 m, respectively; $DF=2$, $F\text{-value}=8.17$, $p\text{-value}<0.001$; Fig. 7).

Case studies illustrating land cover sequences of present-day forest

A map of present-day Baltimore City forest cover highlights four focal areas that we use to illustrate the distinct types of historical land cover sequences across different land ownership classes (Fig. 2). We highlight large, contiguous patches of persistent and successional forest on municipal parkland in Gwynns Falls/Leakin Park and Druid Hill Park (Fig. 2a, b), smaller fragments of successional or converted forest cover that have more recently established on public and private property in the Curtis Bay neighborhood (Fig. 2c), and persistent forest cover on long-standing private institutional properties in the northeast corner of Baltimore City (Fig. 2d). The critical role of public lands in preserving extensive remnant woodlands is immediately apparent, as are the idiosyncratic and relative isolation of other urban forests.

Discussion

Citywide patterns in forest patch histories

In this analysis, we define and characterize patches of persistent forest, successional forest, and forest converted from development over the past century. These types of forest have differing distributions across present-day land ownership categories and different social and ecological characteristics at the patch scale. Over half of Baltimore's present-day forest cover has existed since at least 1927, and almost three-quarters of it has existed since at least 1953. This is in contrast to a recent study from New York, NY which found that the majority of present-day forested natural areas on city parkland were not forested in 1924 or 1951 (Pregitzer et al. 2023).

The age of Baltimore's forested natural areas has important implications for forest composition, structure, and function. We found that persistent forest had the greatest average canopy height, which is consistent with it being the oldest forested area. Persistent forest patches likely have the most

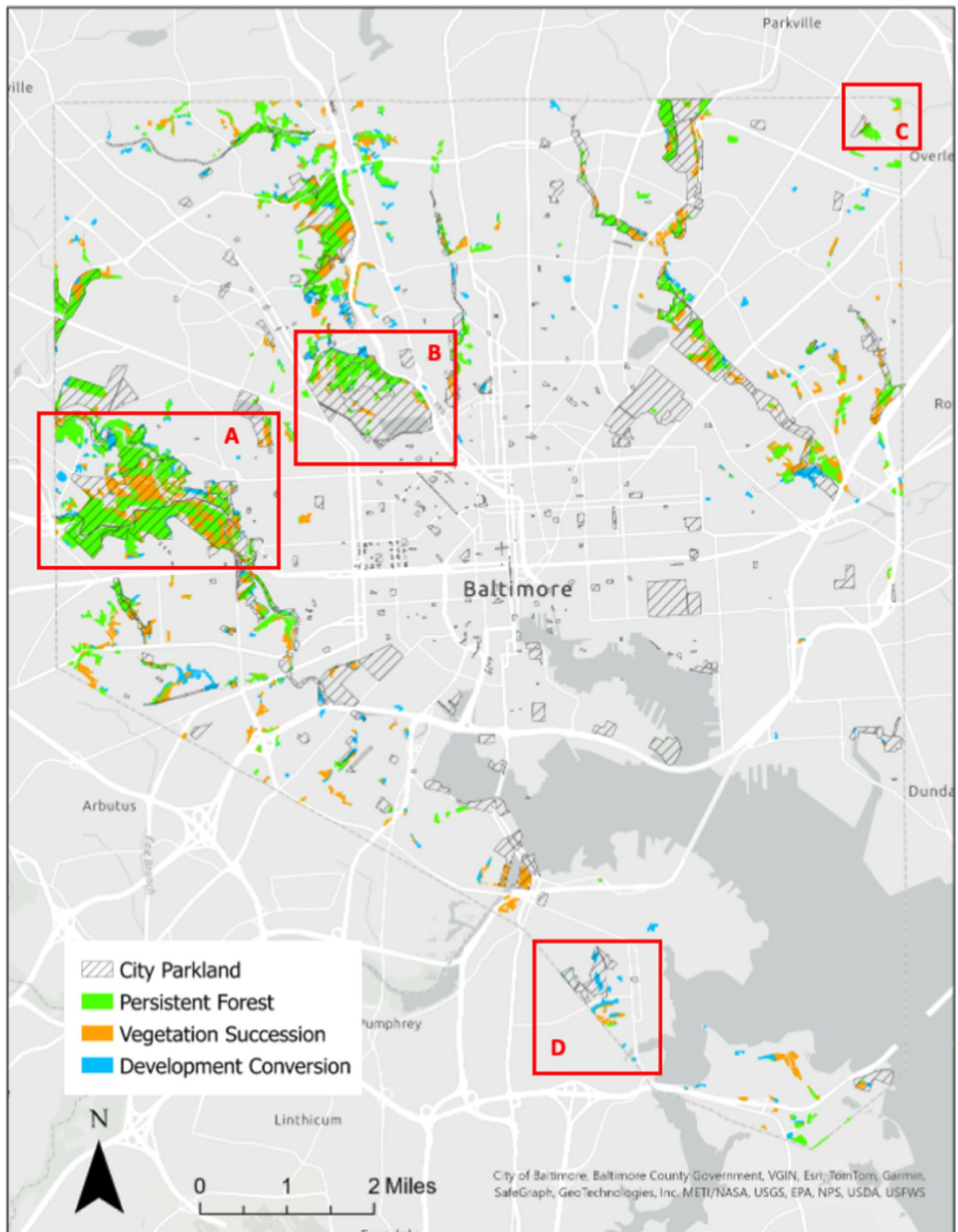


Fig. 2 Present-day forest cover classified by historical land cover sequence class across Baltimore City. Public parkland managed by Baltimore City Recreation & Parks is cross-hatched. Red squares highlight focal areas of interest: **A** Gwynns Falls/Leakin Park, **B** Druid Hill Park, **C** institutionally-owned persistent forest in northeast Baltimore, and **(D)** successional and converted forest cover in the Curtis Bay neighborhood

biomass and store the most carbon, and may also infiltrate more stormwater due to reduced soil disturbance (Archer et al. 2016), provide distinct wildlife habitat, generate greater cooling effects (Zhang et al. 2022), and enhanced levels of other ecosystem services compared to more recent forest cover. Wood biomass is an important sink for both carbon and nitrogen in regenerating forests for at least one century after agricultural abandonment (Hooker and Compton 2003).

Although we did not investigate forest patch species composition in this study, historical land use is known to impact canopy and understory species diversity and composition in urban forest patches. For example, forest sites in New York, NY with a history of human use during the previous 90 years were found to have lower native basal area and higher invasive species groundcover than those that were forested (Pregitzer et al. 2023), and remnant forest patches in Chicago, IL have been shown to have the largest trees and highest levels of oak dominance across the city's urban forest (Fahey and Casali 2017, Darling et al. in press). However, there was no distinction made between previously farmed vs developed land covers in these studies, and the differences between the long-term impacts of such land use and land cover patterns is unknown. Little is known about afforestation on abandoned urban lands, but studies from the northeast United States have documented greater proportions of non-native and early successional species in urban forests found in vacant lots compared to forested parks (Doroski et al. 2022) and in more recently established urban forest patches on vacant land compared to older forest sites (Zipperer 2002). Similar analysis of the species composition and structure of Baltimore's forest patches across historical land cover trajectories is needed to understand whether these dynamics are consistent across metropolitan regions. Furthermore, such information could be used to examine the influence of historical land cover changes on the internal heterogeneity of

individual forest patches, including analysis of forest edge effects and microhabitats.

After persistent forest, succession from non-forest vegetation (grass, shrubland, or agriculture) was the most prevalent historical trajectory for Baltimore's forest patch cover. Processes of secondary succession following agricultural abandonment are well-studied in rural landscapes, documenting progressions from fast-growing pioneer species to longer-lived, shade-tolerant tree species (Howard and Lee 2003), as well as increases in ecosystem carbon sequestration (Post and Kwon 2000; Gough et al. 2016) and shifts in nitrogen cycling dynamics (Trap et al. 2009). Legacies of previous disturbance are known to limit forest carbon sequestration for decades (Gough et al. 2007) and forest canopy may never fully return to pre-disturbance species composition (Foster et al. 1998; Dupouey et al. 2002, Bellemare et al. 2003, Darling et al. in press). However, similar forest chronosequence studies are needed for urban areas, where ongoing human impacts are different than in rural areas and novel species assemblages reflect introduction of cultivated plants (Pregitzer et al. 2019a; Baker et al. 2024).

The amount of Baltimore's present-day forest cover that was non-forest vegetation decreased between 1927 and 1953, which is consistent with the decline of agriculture in the region and the concurrent urban expansion and forest succession (Foresman et al. 1997). A study of forest patch change in Baltimore's Gwynns Falls watershed from 1914 to 2004 found substantial fragmentation and turnover in forest cover over time, despite relative stability in total amount of forest cover (Zhou et al. 2011). Furthermore, the location of dynamic forest change shifted from urban core to surrounding suburban areas over time with shifts in the location of active urbanization. Similar trends were found in the Twin Cities, MN metropolitan region, where suburbanization led to increased forest fragmentation and agricultural abandonment simultaneously led to forest succession over the twentieth century (Berland 2012).

In cities located in forested biomes like Baltimore, forest emergence can occur on public or private land in the absence of active landscape maintenance (Bonney and He 2019; Roman et al. 2021). Areas of Baltimore's present-day forest cover with previous urban development have undergone dynamic land cover changes over the past century. Only about 2%

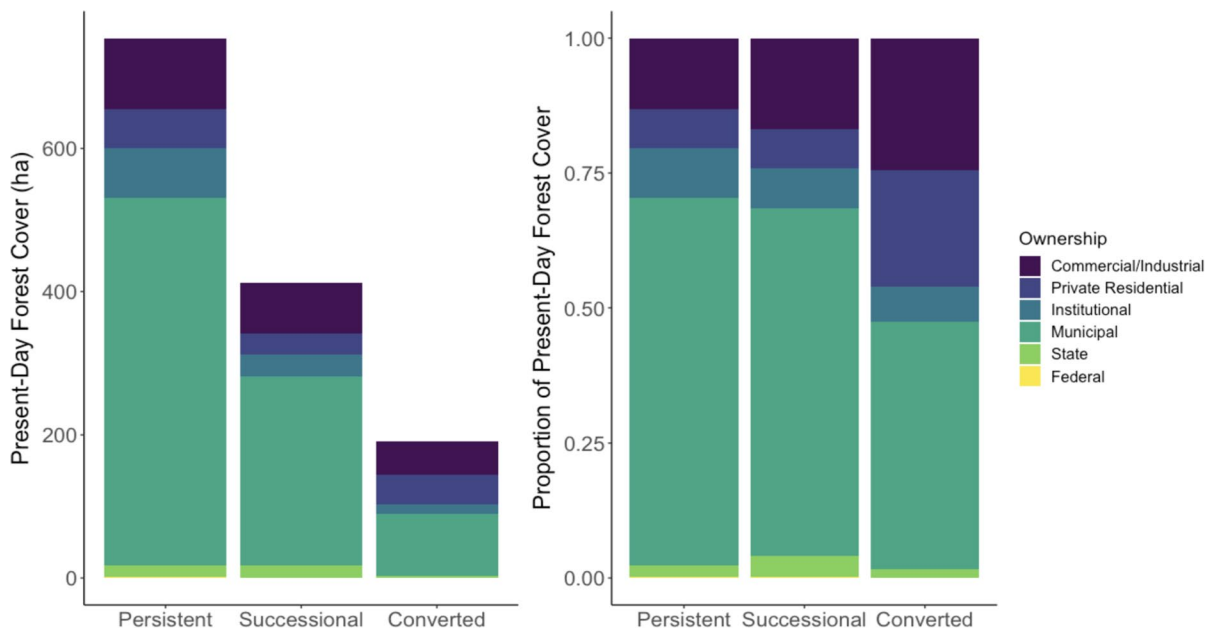
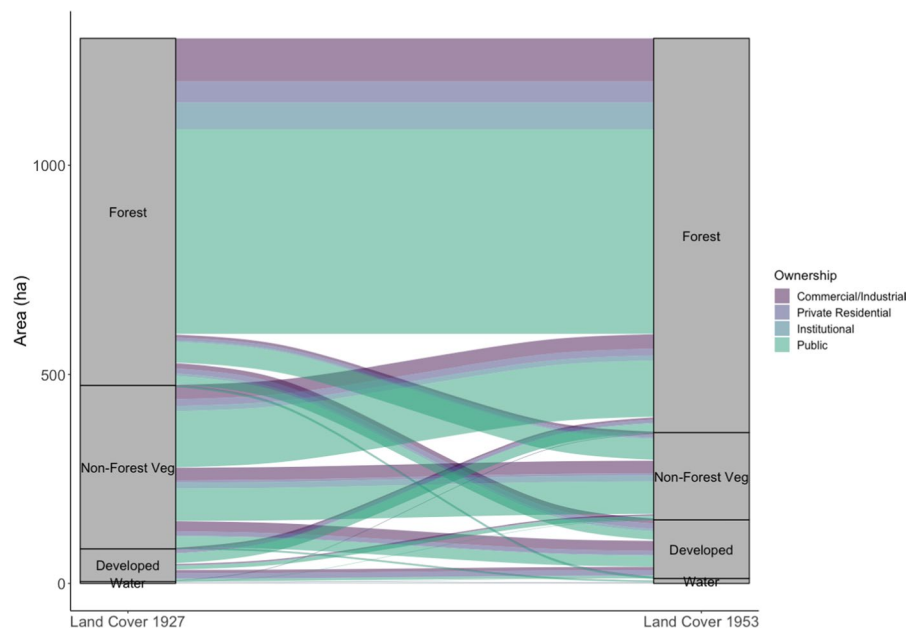


Fig. 3 Area (ha) and percent of present-day (2018) forest cover across six land ownership classes summarized by historical (1927–1953) land cover sequence class. Persistent includes areas classified as forest cover in both 1927 and 1953, Successional involved non-forest vegetation in one or both of those

time periods before reverting to forest in 2018, whereas Converted included developed lands in one or both of those time periods before reverting to forest in 2018

Fig. 4 Sankey diagram depicting historical land cover change (1927–1953) of present-day forest cover by land ownership class in Baltimore, MD. Municipal, state, and federal ownership has been combined into one “public” ownership class for display purposes



of present-day forest had persistent development from 1927 to 1953, while a larger amount (13%) was developed in either 1927 or 1953, moving between

developed, and forest or non-forest vegetation classes over the century before converting to forest by 2018. These forest patches with a history of urban

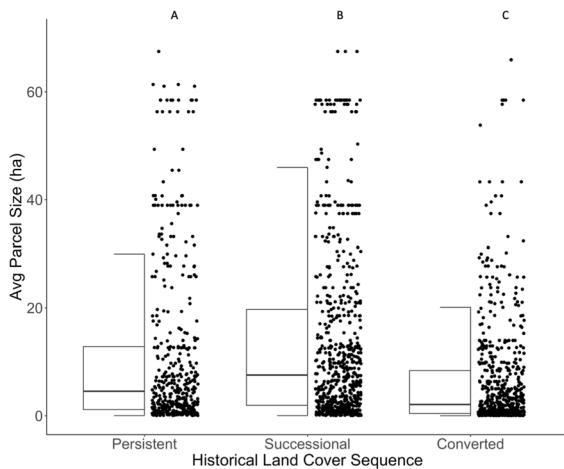


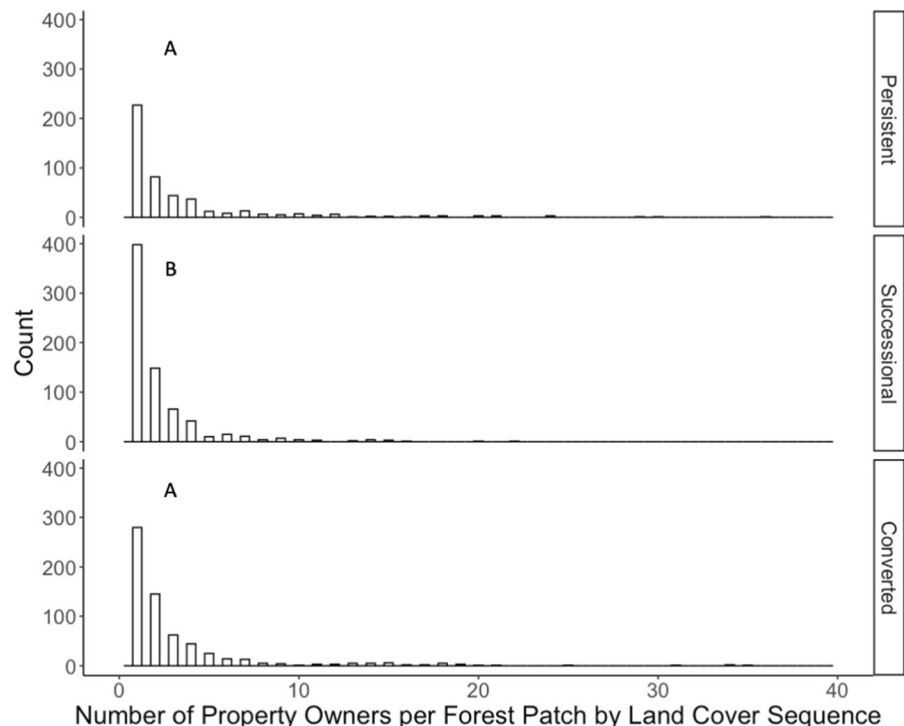
Fig. 5 Average property parcel size (ha) in present-day forest patches of Baltimore, MD by historical land cover sequence. Box plots depict median and interquartile range; outliers have been removed from plots. Letters show significant differences between historical land cover sequence classes ($p < 0.05$)

development are more likely to be found on commercial/industrial or private residential land, whereas persistent and successional forest is more likely to be municipally owned. This pattern both confirms the

importance of large tracts of forest on public lands, but also highlights the existence of dynamic patches of emergent forest on private lands across a variety of ownerships and management regimes. It is important to note that not all municipally-owned forest occurs on city parkland. Forest cover also exists on land owned by other city agencies (e.g., Housing & Community Development, Baltimore City Public Schools, Department of Transportation) that may lack staff with natural resource expertise required for effective forest management. Publicly owned forest outside of parkland may be more vulnerable to development, but even forested areas on parkland can be subject to canopy loss from infrastructure projects (Bowers et al. 2020).

Conservation of forest patches across multiple property parcels may be more legally and logistically challenging, yet they do make up a significant amount of the city's forest and may be important to consider for citywide conservation planning and forest habitat connectivity (Avins 2013; Morzillo et al. 2022). City-wide analysis by patch size and by number and type of property owners can assist land trusts and community organizations in clarifying who has legal decision-making power over forest patches and determine

Fig. 6 Count of unique property owners in present-day forest patches of Baltimore, MD by historical land cover sequence class. Letters indicate significant differences between sequence classes ($p < 0.05$)



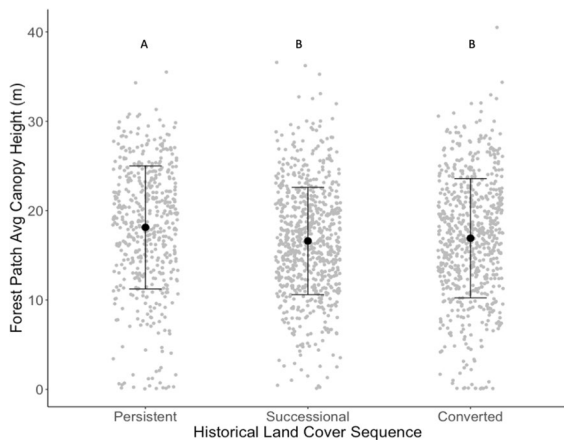


Fig. 7 Average tree canopy height (m) within present-day forest of Baltimore, MD by historical land cover sequence class. Each point represents average canopy height of a contiguous forest patch and the mean of each historical land cover sequence class is represented by the black dot ($\pm$ SE). Letters indicate significant differences between sequence classes ($p < 0.05$)

ways in which community support or advocacy may influence their conservation and management. Baltimore's forest patches converted from previously developed land are composed of a larger number of smaller parcels, whereas persistent and successional forest patches are composed of fewer, larger parcels. However, because persistent patches are the largest, they have the most individual property owners per patch, on average. Successional patches have the largest average parcel size and intermediate patch size and so have the fewest property owners per patch. Converted patches have the smallest average patch and parcel size and so have an intermediate number of individual property owners. Further analysis of the interaction between historical land cover and present-day property ownership may contribute to strategies for enhancing urban forest connectivity and ecological networks through landscape conservation planning and design.

Historical context is notably absent from recent syntheses of urban landscape ecology (Breuste et al. 2008; Francis et al. 2016; Muderere et al. 2018) but provides a layer of information that can inform sound environmental policy and planning. A historical perspective can inform management approaches and conservation priorities with limited resources available for sustaining urban natural resources. To this

end, the historical land cover trajectories of Baltimore's present-day forest are now available to view and download in an ArcGIS Online application (Sonti and Baker 2023). Historical information can also be a powerful tool for environmental education and advocacy. The historical aerial imagery and land-use/land cover classification presented here have been used to generate individual forest patch histories for local environmental stewards who work with Baltimore Green Space to care for forest patch sites in their neighborhoods. This information provides additional context for the structure, function, and biodiversity that the stewards observe on the ground, and can help foster meaningful exchanges between scientists, environmental advocates, and community members.

Focal areas illustrate historical trajectories on public and private lands

Although highly urbanized areas often have the greatest degree of forest conversion and fragmentation relative to pre-colonial vegetation patterns, the forests that remain in these areas may also have a greater degree of protection (Fahey and Casali 2017). For example, large areas of persistent forest in Baltimore's Druid Hill Park and Gwynns Falls/Leakin Park reflect the long history of municipal parkland preservation. Druid Hill Park was a private family estate purchased by the City of Baltimore in 1860 and is one of the oldest large public parks in the United States (City of Baltimore 2023a). The City left the existing mature forest in the northern part of the park, rather than landscaping it and maintaining open areas of non-forest vegetation as in the southern portion of the park. The small amounts of succession from non-forest vegetation to forest throughout the park likely result from areas where grassy lawns or sheep pasture were allowed to revert to forest. The City established Gwynns Falls Park in 1908 as another large public natural area and added Leakin Park in the 1940s. In a 1904 report for Baltimore City, the Olmsted Brothers Landscape Architects firm recommended establishing the stream valley park for its remarkable beauty, for urban flood management, and for scenery "of a picturesque and sylvan sort seldom possible to retain so near a great city" (Friends of Maryland's Olmsted Parks 2002; City of Baltimore 2023b). Part of the reason such a large amount of area was preserved is that the park occupies some of the most rugged landscape

in the region, making it some of the least desirable land for agriculture and residential development (Bain and Buckley 2019). Large areas of successional forest and forest converted from development show where the existing forest was allowed to expand as agricultural or developed areas returned to forest (Lagrosa et al. 2021a, 2022a). The forest of Gwynns Falls/Leakin Park was threatened by the development of Interstate 70 during the 1970s but years of coordinated resistance by local citizens blocked plans to route the highway through the park (Bain and Buckley 2019). Parts of these forest patches are now well over a century old, and provide social and biophysical ecosystem services that would take generations to replace if they were cut down, highlighting the importance of continued preservation and management of these urban natural areas.

Within private ownership classes, institutional land made up a greater relative proportion of stable forest or non-forest vegetation from 1927 to 1953 and was less prevalent in the dynamic land cover classes that changed between 1927 and 1953. The northeast corner of Baltimore contains several patches of persistent forest on institutional land. Parkwood Cemetery lies in the very northeast corner of the city and began operating in 1919 (The Sun 1919) and the Maryland School for the Blind lies slightly southwest and established their campus in 1907 (Maryland School for the Blind 2023). These long-standing Baltimore institutions were able to preserve forest canopy alongside the other land uses on their property. The Maryland School for the Blind placed almost 20 acres of land into a Forest Conservation Easement in 2013, demonstrating their commitment to continued preservation and restoration of the forest on their property.

The final focal area that we chose to highlight was Baltimore's Curtis Bay neighborhood, which illustrates forest patches converted from previous industrial development. Farring Baybrook Park was originally the site of temporary housing for wartime industrial workers at Fairfield Yards making Liberty ships (City of Baltimore 2008). The park was established in the 1970s when the barracks were torn down to create residential neighborhoods (City of Baltimore 2008). Both inside and outside the park boundaries, there are now forested natural areas where remnant clusters of tree cover on agricultural and developed land were allowed to expand over time (Lagrosa et al. 2021a, 2022a). Relatively speaking, there is not a lot

of forest in this part of the city. Therefore, areas of more recently established forest cover may provide sites for maintaining critical access to natural spaces and ecosystem services for residents of surrounding neighborhoods.

Conclusion

Even the most densely populated cities can contain extensive natural areas, contributing unique biodiversity and ecosystem services to the urban environment (Pregitzer et al. 2019a, b). Baltimore City has a substantial amount of forest cover approaching or exceeding a century in age, much of which is found on public lands and needs continued conservation and management in order to sustain its ecosystem function. Although older forest in Baltimore generally has greater canopy height and likely provides enhanced ecosystem services such as carbon storage, air temperature reduction, and stormwater retention, there is a substantial amount of forest more recently converted from developed lands and agricultural fields that is on its way to becoming more established. These converted and successional forest patches can provide unique social and environmental benefits to neighborhoods with fewer natural areas and less canopy cover. However, forested areas on both public and private lands are vulnerable to canopy loss from development and infrastructure projects (Bowers et al. 2020). Recent Baltimore City legislation seeks to protect forested natural areas for their unique ecosystem service contributions in the face of development pressures, climate change, and other anthropogenic impacts. As of 2020, the minimum size threshold to trigger forest conservation regulations in Baltimore City has been reduced from 20,000 square feet to 5000 square feet of disturbance, forest stand delineations are required as part of an approved forest conservation plan, and fines and mitigation fees have been increased (Baltimore Green Space 2023). These protections will help minimize development impacts to critical urban forest cover, which can take decades to recover. Using the historical landscape analysis presented here, urban forest patches could be further prioritized for protection by their age and associated ecosystem qualities such as canopy height, species composition, and soil conditions. The forest cover of cities changes over time with ongoing natural and

anthropogenic processes of succession, canopy gap formation, development, and tree planting. Analyses such as the one presented here may be repeated longitudinally to examine the historical land cover of areas of recent forest loss or gain, and to assess rates of persistent forest loss compared to loss of successional or development conversion forest. Over time, these data may provide further insights into the efficacy of present-day conservation policy and management activities in the face of climate change and other anthropogenic impacts to urban forest cover.

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Declarations

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References

- Alfaro-Sánchez R, Jump AS, Pino J, Díez-Nogales O, Espelta JM (2019) Land use legacies drive higher growth, lower wood density and enhanced climatic sensitivity in recently established forests. *Agric for Meteorol* 276:107630
- Alonzo M, Baker ME, Gao Y, Shandas V (2021) Spatial configuration and time of day impact the magnitude of urban tree canopy cooling. *Environ Res Lett* 16(8):084028
- Anderson JR, Hardy EE, Roach JT, Witmer RE (1976) A land-use and land cover classification system for use with remote sensor data, Geological survey professional paper 964; United States Department of the Interior, United States Geological Survey
- Archer NA, Otten W, Schmidt S, Bengough AG, Shah N, Bonell M (2016) Rainfall infiltration and soil hydrological characteristics below ancient forest, planted forest and grassland in a temperate northern climate. *Ecohydrology* 9(4):585–600
- Avins M (2013) Baltimore's Forest Patches: emerald assets for ecosystem services. Baltimore Green Space, Baltimore, MD. <https://baltimoregreenspace.org/wpcontent/uploads/2014/08/ForestPatchesWeb.pdf>
- Bain DJ, Buckley GL (2019) The history and legacies of mercantile, industrial, and sanitary transformations. In: Pickett STA, Cadenasso ML, Grove JM, Irwin EG, Rosi-Marshall EJ, Swan CM (eds) *Science for the sustainable city: empirical insights from the Baltimore school of urban ecology*. Yale University Press, New Haven, pp 47–60
- Baker ME, Yesilonis I, Templeton L, Shobe B, Bos J, Sonti NF, Lautar K (2024) Distributed urban forest patch characterization detects edge effects and patterns of ecosystem diversity for monitoring and management. *Ecosphere* (in press)
- Baltimore Green Space (2023) Advocacy. <https://baltimoregreenspace.org/advocacy/>. Accessed 7 Aug 2023
- Baltimore Office of Sustainability (2023) Forest conservation. <https://www.baltimoresustainability.org/permits/forest-conservation/>. Accessed 7 Aug 2023
- Bellemare J, Motzkin G, Foster DR (2002) Legacies of the agricultural past in the forested present: an assessment of historical land-use effects on rich mesic forests. *J Biogeogr* 10–11:1401–1420
- Benitez JA, Fisher TR (2004) Historical land-cover conversion (1665–1820) in the Choptank watershed, eastern United States. *Ecosystems* 7(3):219–232
- Berland A (2012) Long-term urbanization effects on tree canopy cover along an urban–rural gradient. *Urban Ecosyst* 15:721–738
- Bonney MT, He Y (2019) Attributing drivers to spatio-temporal changes in tree density across a suburbanizing landscape since 1944. *Landsc Urban Plan* 192:103652
- Boone CG, Buckley GL, Grove JM, Sister C (2009) Parks and people: an environmental justice inquiry in Baltimore, Maryland. *Ann Assoc Am Geogr* 99(4):767–787
- Bossuyt B, Hermy M (2001) Influence of land use history on seed banks in European temperate forest ecosystems: a review. *Ecography* 24(2):225–238

- Bowers AA, Gilder-Busatti AL, Lautar KJ (2020) Preservation, regulations, and policy to protect and grow Baltimore's forests. *Cities Environ* 13(1):22
- Breuste J, Niemelä J, Snep RP (2008) Applying landscape ecological principles in urban environments. *Landsc Ecol* 23:1139–1142
- Brooks NA, Rockel EG, Hughes WC (1979) A history of Baltimore County. Friends of the Towson Library, Towson
- Brush GS, Lenk C, Smith J (1980) The natural forests of Maryland: an explanation of the vegetation map of Maryland. *Ecol Monogr* 50(1):77–92
- Buckley GL (2010) America's conservation impulse. University of Virginia Press, Charlottesville
- Chesapeake Bay Program (2022) Chesapeake bay land use and land cover database 2022 edition: land use/land cover: U.S. Geological Survey data release. Developed by the Chesapeake Conservancy, U.S. Geological Survey and University of Vermont Spatial Analysis Lab. <https://doi.org/10.5066/P981GV1L>
- Chesapeake Bay Program (2023) Tree cover status & change for Baltimore City, MD. [https://cicwebresources.blob.core.windows.net/tc-factsheets/Tree%20Cover%20Fact%20Sheet%20Baltimore%20\(city\)%2C%20MD%202013-2018.pdf](https://cicwebresources.blob.core.windows.net/tc-factsheets/Tree%20Cover%20Fact%20Sheet%20Baltimore%20(city)%2C%20MD%202013-2018.pdf). Accessed 7 Aug 2023
- City of Baltimore Department of Recreation and Parks (2008) Farring Baybrook Park Master Plan. <https://bcrp.baltimorecity.gov/sites/default/files/Farring%20Baybrook%20Master%20Plan.pdf>. Accessed 7 Aug 2023
- City of Baltimore Department of Recreation and Parks (2023a) Druid Hill Park. <https://bcrp.baltimorecity.gov/parks/druid-hill>. Accessed 7 Aug 2023
- City of Baltimore Department of Recreation and Parks (2023b) Gwynns Falls/Leakin Park. <https://bcrp.baltimorecity.gov/parks/gwynns-falls>. Accessed 7 Aug 2023
- Crenson MA (2019) Baltimore: a political history. The Johns Hopkins University Press, Baltimore
- Darling L, Locke D, Rollinson C, Schmit JP, Morzillo A, Johnson M, Fahey R, Johnson L, Baker M, Hardiman B Ecological and segregationist histories impact access to ecosystem services from forests
- Doroski DA, Bradford MA, Duguid MC, Hallett RA, Pregitzer CC, Ashton MS (2022) Diverging conditions of current and potential future urban forest patches. *Ecosphere* 13(3):e4001
- Dupouey JL, Dambrine E, Laffite JD, Moares C (2002) Irreversible impact of past land use on forest soils and biodiversity. *Ecology* 83(11):2978–2984
- Fahey RT, Casali M (2017) Distribution of forest ecosystems over two centuries in a highly urbanized landscape. *Landsc Urban Plan* 164:13–24
- Flinn KM, Vellend M (2005) Recovery of forest plant communities in post-agricultural landscapes. *Front Ecol Environ* 3(5):243–250
- Foresman TW, Pickett ST, Zipperer WC (1997) Methods for spatial and temporal land-use and land cover assessment for urban ecosystems and application in the greater Baltimore-Chesapeake region. *Urban Ecosyst* 1(4):201–216
- Foster DR, Motzkin G, Slater B (1998) Land-use history as long-term broad-scale disturbance: regional forest dynamics in central New England. *Ecosystems* 1:96–119
- Francis RA, Millington JDA, Chadwick MA (2016) Introduction: an overview of landscape ecology in cities. In: Francis RA, Millington JDA, Chadwick MA (eds) *Urban landscape ecology: science, policy and practice*. Routledge, New York, pp 1–18
- Friends of Maryland's Olmsted Parks (2002) 1904 Olmsted Bros. Report: The Advancement of City Planning in Baltimore. http://www.olmstedmaryland.org/wp-content/uploads/2012/07/FMOPL_1904Plan.pdf. Accessed 7 Aug 2023
- Gough CM, Vogel CS, Harrold KH, George K, Curtis PS (2007) The legacy of harvest and fire on ecosystem carbon storage in a north temperate forest. *Glob Change Biol* 13(9):1935–1949
- Gough CM, Curtis PS, Hardiman BS, Scheuermann CM, Bond-Lamberty B (2016) Disturbance, complexity, and succession of net ecosystem production in North America's temperate deciduous forests. *Ecosphere* 7(6):e01375
- Healy M, Rogan J, Roman LA, Nix S, Martin DG, Geron N (2022) Historical urban tree canopy cover change in two post-industrial cities. *Environ Manage* 70(1):16–34
- Hooker TD, Compton JE (2003) Forest ecosystem carbon and nitrogen accumulation during the first century after agricultural abandonment. *Ecol Appl* 13(2):299–313
- Howard LF, Lee TD (2003) Temporal patterns of vascular plant diversity in southeastern New Hampshire forests. *For Ecol Manage* 185(1–2):5–20
- Irwin EG, Buckley GL, Gnagey M, Irwin N, Newburn D, Pierce E, Wrenn D, Zhang W (2019) The role of regulations and norms in land use change. In: Pickett STA, Cadenasso ML, Grove JM, Irwin EG, Rosi-Marshall EJ, Swan CM (eds) *Science for the sustainable city: empirical insights from the Baltimore school of urban ecology*. Yale University Press, New Haven, pp 112–131
- Johnson LR, Johnson ML, Aronson MF, Campbell LK, Carr ME, Clarke M, D'Amico V, Darling L, Erker T, Fahey RT, King KL (2021) Conceptualizing social-ecological drivers of change in urban forest patches. *Urban Ecosyst* 24:633–648
- Kaye JP, Groffman PM, Grimm NB, Baker LA, Pouyat RV (2006) A distinct urban biogeochemistry? *Trends Ecol Evol* 21(4):192–199
- Kvit A, Corrigan AE, Locke DH, Curriero FC, Mmari K (2022) Can restoring vacant lots help reduce crime? An examination of a program in Baltimore, MD. *Urban for Urban Green* 74:127630
- JJLagrosaIVNFSontiJMGrove2021Georectified mosaic of aerial images of Baltimore City in 1927 ver 1Environ Data Initiative10.6073/pasta/045e3001129aca3b34fd0e91b1a6f596Lagrosa JJ IV, Sonti NF, Grove JM (2021a) Georectified mosaic of aerial images of Baltimore City in 1927 ver 1. Environ Data Initiative. <https://doi.org/10.6073/pasta/045e3001129aca3b34fd0e91b1a6f596>
- JJLagrosaIVNFSontiJMGrove2021A land-use/land cover classification of Baltimore City in 1927 ver 1Environ Data Initiative10.6073/pasta/28793d6417db548f26679ab0e5197fb8Lagrosa JJ IV, Sonti NF, Grove JM (2021b) A land-use/land cover classification of Baltimore City in 1927 ver 1. Environ Data Initiative. <https://doi.org/10.6073/pasta/28793d6417db548f26679ab0e5197fb8>
- JJLagrosaIVNFSontiJMGrove2022Georectified mosaic of aerial images of Baltimore City in 1953 ver 1Environ Data

- Initiative10.6073/pasta/6b583e08366f53fd8665e835f1bad44cLagrosa JJ IV, Sonti NF, Grove JM (2022a) Georectified mosaic of aerial images of Baltimore City in 1953 ver 1. Environ Data Initiative. <https://doi.org/10.6073/pasta/6b583e08366f53fd8665e835f1bad44c>
- JJLagrosaIVNFSontiJMGrove2022A land-use/land cover classification of Baltimore City in 1953Environ Data Initiative10.6073/pasta/84b59c8e375e3915cc62dea2cf73627aLagrosa JJ IV, Sonti NF, Grove JM (2022b) A land-use/land cover classification of Baltimore City in 1953. Environ Data Initiative. <https://doi.org/10.6073/pasta/84b59c8e375e3915cc62dea2cf73627a>
- Locke DH, Roman LA, Henning JG, Healy M (2023) Four decades of urban land cover change in Philadelphia. *Landsc Urban Plan* 236:104764
- Maryland School for the Blind (2023) History. <https://www.marylandschoolfortheblind.org/welcome-to-msb/about-us/history/>. Accessed 7 Aug 2023
- Morzillo AT, Campbell LK, King KL, Lautar KJ, Scott L, Johnson ML, Clarke M, Rhodes L, Pincetl S, Sonti NF, Locke DH (2022) A tale of urban forest patch governance in four eastern US cities. *Urban for Urban Green* 75:127693
- Muderere T, Murwira A, Tagwireyi P (2018) An analysis of trends in urban landscape ecology research in spatial ecological literature between 1986 and 2016. *Current Landsc Ecol Rep* 3:43–56
- Nix S, Roman LA, Healy M, Rogan J, Pearsall H (2022) Linking tree cover change to historical management practices in urban parks. *Landsc Ecol* 38:1–19
- Ogden LA, Aoki C, Grove JM, Sonti NF, Hall W, Locke D, Pickett STA, Avins M, Lautar K, Lagrosa J (2018) Landscape ethnography: an approach to study the environmental history and political ecology of urban forests. *Urban Ecosyst*. <https://doi.org/10.1007/s11252-018-0744-z>
- Post WM, Kwon KC (2000) Soil carbon sequestration and land-use change: processes and potential. *Glob Change Biol* 6(3):317–327
- Pregitzer CC, Charlop-Powers S, Bibbo S, Forgione HM, Gunther B, Hallett RA, Bradford MA (2019a) A city-scale assessment reveals that native forest types and overstory species dominate New York City forests. *Ecol Appl* 29(1):e01819
- Pregitzer CC, Charlop-Powers S, McCabe C, Hipple A, Gunther B, Bradford MA (2019b) Untapped common ground: the care of forested natural areas in American Cities. 46pp. Natural Areas Conservancy.
- Pregitzer CC, Bradford MA (2023) Associations between recent land use history and urban forest composition. *Urban for Urban Green* 90:128134
- Roman LA, Fristensky JP, Eisenman TS, Greenfield EJ, Lundgren RE, Cerwinka CE, Hewitt DA, Welsh CC (2017) Growing canopy on a college campus: understanding urban forest change through archival records and aerial photography. *Environ Manage* 60:1042–1061
- Roman LA, Catton IJ, Greenfield EJ, Pearsall H, Eisenman TS, Henning JG (2021) Linking urban tree cover change and local history in a post-industrial city. *Land* 10(4):403
- Sonti NF (2020) Ambivalence in the Woods: Baltimore resident perceptions of local forest patches. *Soc Nat Resour* 33(7):823–841
- Sonti N, Baker M (2023) The urban forest patch viewer app. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. <https://experience.arcgis.com/experience/e9801ba79ba0487c8a027390da49fbae>. Accessed 15 Sep 2023
- The Sun (1919) New Cemetery is Proposed. *The Sun* (Baltimore, Maryland) 18 Nov 1919: p.22, col. 2. Digital archives. newspapers.com. Accessed 7 Aug 2023.
- Threlfall CG, Kendal D (2018) The distinct ecological and social roles that wild spaces play in urban ecosystems. *Urban for Urban Green* 29:348–435
- Trap J, Bureau F, Vincelas-Akpa M, Chevalier R, Aubert M (2009) Changes in soil N mineralization and nitrification pathways along a mixed forest chronosequence. *For Ecol Manage* 258(7):1284–1292
- U.S. Census Bureau (2021) Population, Census, April 1, 2020. <https://www.census.gov/quickfacts/>. Accessed 7 Aug 2023
- Vogt P, Riitters KH, Estreguil C, Kozak J, Wade TG, Wickham JD (2007) Mapping spatial patterns with morphological image processing. *Landsc Ecol* 22:171–177
- Zhang Z, Li X, Liu H (2022) Biophysical feedback of forest canopy height on land surface temperature over contiguous United States. *Environ Res Lett* 17(3):034002
- Zhou W, Huang G, Pickett ST, Cadenasso ML (2011) 90 years of forest cover change in an urbanizing watershed: spatial and temporal dynamics. *Landsc Ecol* 26:645–659
- Zipperer WC (2002) Species composition and structure of regenerated and remnant forest patches within an urban landscape. *Urban Ecosyst* 6:271–290
- Zipperer WC, Foresman TW, Walker SP, Daniel CT (2012) Ecological consequences of fragmentation and deforestation in an urban landscape: a case study. *Urban Ecosyst* 15:533–544

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