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Research Paper

Whose woods are these? Forest patch characteristics and ownership across cities of the eastern United States

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HIGHLIGHTS

- Forest patch distribution and ownership impact conservation and management.
- We map forest patches of three cities using morphological spatial pattern analysis.
- Spatial characteristics and ownership of forest patches vary by city.
- Patterns reflect historical and present-day processes of local ecology and development.
- Baltimore has the highest % land area covered by forest and % privately-owned forest.

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ABSTRACT

Forests in cities are important social and ecological resources that vary in spatial extent, configuration, and ownership across urban areas, yet these patterns are not well described. Using high resolution urban tree canopy maps and planimetric data from three major cities of the eastern United States (New York, NY; Philadelphia, PA; Baltimore, MD), we distinguish patches of forest from other tree canopy types. We then compare forest patch spatial characteristics and ownership across the three cities. Baltimore has the greatest citywide forest patch cover (8.3 %) and forest patch area per resident (29.5 m^2/person), followed by Philadelphia (6.3 % and 13.7 m^2/person) and New York City (3.9 % and 3.5 m^2/person). Baltimore's forest also has the largest median patch sizes, and the lowest citywide forest edge to core ratio. Thus, we find Baltimore's forest cover to be more concentrated and less fragmented than the other two cities. While all cities have a majority of forest patch area located on municipal property, Baltimore has the greatest amount of privately owned forest, followed by Philadelphia and then NYC. Baltimore also has the largest number of property parcels and owner types per patch compared to the other two cities. These patterns in distribution of forest cover reflect historical and present-day processes of local ecology and economic development, and have implications for effective conservation and management of forests in cities.

1. Introduction

Forested natural areas exist throughout urban landscapes and can provide unique ecosystem services to city residents (Threlfall & Kendal, 2018; Johnson et al., 2021). Resources for inventory and management of these natural areas are generally limited and often focuses only on public parkland (Pregitzer et al., 2021). Yet, these urban wild spaces can be found throughout many land uses and ownerships (Threlfall & Kendal, 2018; Morzillo et al., 2022). Cities may vary in the amount, configuration, and ownership of forested natural areas that they contain, but this is not well described. These characteristics can have important implications for land conservation and for community use of such unique urban green spaces. Without a complete picture of the distribution of forest cover across different land uses and ownerships, it is difficult to

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develop effective policy to guide management, especially outside of public lands (Vallejo et al. 2024).

Many cities use assessments of all urban tree canopy cover (UTC), reported as a percentage of total land area within a city's boundaries. This common metric serves as a baseline for setting overall canopy coverage goals. For example, among U.S. cities, Baltimore has a goal of reaching 40 % tree canopy cover by 2037, Philadelphia has a goal of reaching 30 % tree canopy cover by 2050, and New York City's Forest For All Coalition has a goal of 30 % canopy cover by 2035 (City of Baltimore, 2019; City of Philadelphia, 2023; Treglia et al., 2022). However, most UTC coverage maps do not differentiate canopy cover types within an urban area (e.g., street trees, parks, residential yards, forest patches; see Fig. 1). The distinctions between these urban tree site types and land ownerships have major implications for policy, management, and distribution of benefits of trees and forests in the city. An analysis of UTC by land use in ten U.S. cities revealed that parks have the greatest tree canopy coverage followed by single-family residential land use; however, this analysis did not distinguish natural areas from landscaped green space (Stuhlmacher et al., 2025). Recently, the availability of high-resolution land cover data has allowed for the identification of forested areas within cities that are likely to have natural processes of decomposition and regeneration occurring in the understory (O'Neil-Dunne et al., 2014; CBPO, 2022). However, these resource-intensive maps require many more data inputs and manual corrections than a simple tree canopy map and, as a result, are not widely available.

Researchers have investigated ecological properties and functions of urban forest patches, including plant biodiversity (Trammell et al., 2020), wildlife (Kang et al., 2015), soil properties (Phillips et al., 2019), regeneration (Piana et al., 2021), and tree physiology (Sonti et al., 2021). While it is recognized that forests in cities are owned and managed through a variety of governance structures (Morzillo et al., 2022), little is known about overall size or distribution of forest land ownership within or between cities. Rural forest ownership is known to correlate with ecological characteristics such as forest structure, carbon storage, and understory plant composition (Bergès et al., 2013; Schaich & Plieninger, 2013). A better understanding of urban forest patch characteristics and patterns of ownership across cities may be used to inform and prioritize present-day conservation and management efforts across public and private lands (Aronson et al., 2017; Lawson & Plitt, 2023).

The objective of this study was to compare forest canopy cover, patch characteristics, and forest land ownership across three major cities of the eastern United States (New York, NY; Philadelphia PA; and Baltimore, MD). These cities provide a compelling study area, given their similar physiographic position and early patterns of urban development, followed by divergent recent economic conditions. All three cities have a similar geographic position (edge of the Northern Piedmont within the Eastern Deciduous Forest) and early histories of industrialization and urban development following European settlement, including the establishment of large public parks in the mid-nineteenth to early twentieth centuries. While all three cities are now post-industrial, the cities diverge in their recent histories of economic development and population growth or decline. New York City (NYC) is the nation's most populous city with the largest economy and most densely built landscape, while Baltimore's population has been in decline since 1950 and the city currently has a large number of vacant properties (Locke et al., 2023). Philadelphia's population density and economic trajectory lies somewhere in between these two extremes. We expected to find variation in the distribution of forest cover across public and private ownership types, reflecting processes of local ecology and historical development in each city. Specifically, we expected to find that the distribution of large public forested areas might be constrained by physiographic factors, such as shallow soils associated with rock outcroppings or steep-sloped river valleys. In contrast, we expected smaller privately owned forest cover to be more evenly distributed within each city. We also expected to find the greatest proportion of forest in private ownership in Baltimore, which has a large number of vacant properties and the lowest population density. We expected to find the lowest proportion of privately owned forest in NYC (the largest city with the highest population density) and expected Philadelphia to fall somewhere in between.

2. Methods

2.1. Study area

The study area for this analysis included the land surface area within the city limits of New York, NY; Philadelphia, PA; and Baltimore, MD. All three cities are located in the mid-Atlantic region of the U.S. within the mixed hardwood forest where oak is dominant. Baltimore and Philadelphia are divided between Piedmont Uplands and Atlantic Coastal Plain ecoregions while NYC is divided between Northern Piedmont and Northeastern Coastal Zone ecoregions. The climate of these

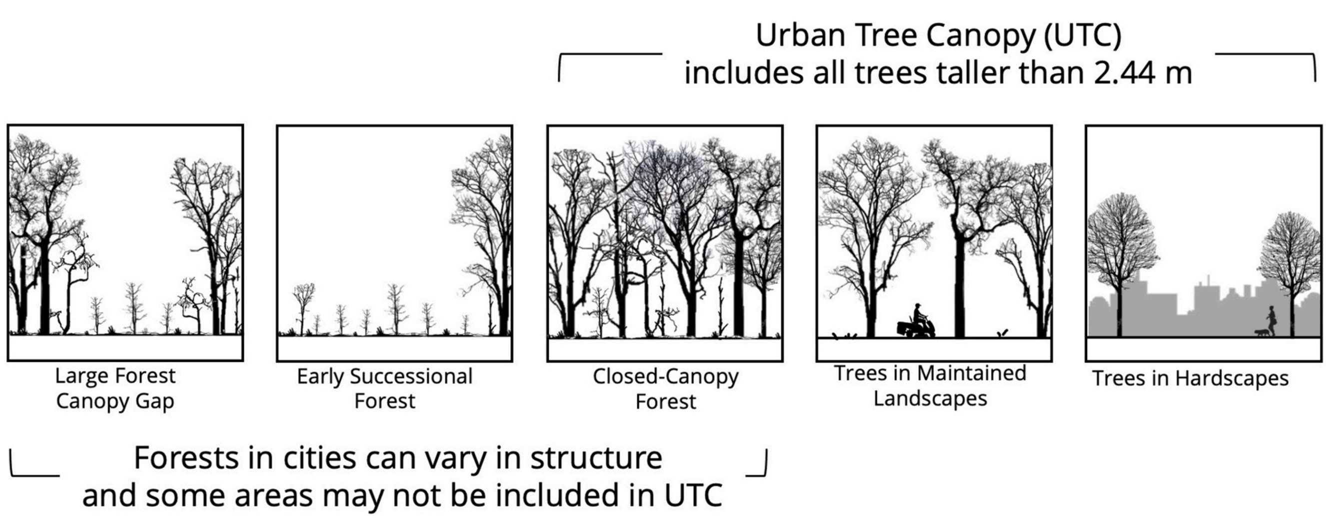

Fig. 1. Urban tree canopy (UTC) includes all vegetation that is greater than 2.44 m tall and includes trees in different urban landscape types, including natural areas, maintained landscapes (e.g., residential yards, landscaped parks and institutional grounds), and hardscapes (e.g., street trees, medians, plazas). Forests in cities can vary in structure, and sites where mature canopy trees are not present, such as large forest canopy gaps and early successional forests, may not be included in UTC maps following this height definition.

eastern U.S. cities is strongly seasonal with warm summers and cold winters and all three cities receive ~1100 mm precipitation annually (NOAA, 2018). The three cities also occupy a latitudinal gradient, with progressively warmer average annual air temperatures as you move south from NYC (12.9 °C annual avg) to Philadelphia (13.3 °C annual avg) to Baltimore (14.7 °C annual avg). New York City is much larger in land area and population than Philadelphia, which is larger than Baltimore City, and the three cities follow the same pattern in terms of population density (Table 1). Baltimore has the highest urban tree canopy cover at 28 % with NYC's 22 % tree canopy cover slightly higher than Philadelphia's 20 % canopy cover.

Aligning with regional land use history (Stroud, 2012), the three cities have a similar history of land clearing for agriculture and timber harvesting following European settlement in the seventeenth century. The following centuries saw transition from agriculture to industrial economies, allowing reforestation of formerly cleared lands. All three cities established large municipal parks with substantial forest cover from the mid-nineteenth century into the early twentieth century. The three cities were among the top ten most populous cities in the United States throughout the first half of the twentieth century, with thriving economies driving the expansion of urban development. However, Baltimore and Philadelphia experienced peak population in 1950, after which both cities began to experience prolonged periods of population decline. Philadelphia has again experienced population growth in the first part of the twenty-first century, while Baltimore's population continues to decrease. New York City has experienced population drops and gains over the latter half of the twentieth century, but remains the nation's largest city with the highest population density by far. Expansion of some forested natural areas in Philadelphia during the second half of the twentieth century has been attributed, in part, to dis-investment in urban parkland and mowing cessation, allowing tree regeneration and canopy expansion into previously landscaped areas (Roman et al., 2021; Nix et al., 2023). Similar processes may explain the expansion of forest cover on NYC parkland during the second half of the twentieth century (Pregitzer & Bradford, 2023). As the least densely developed city, Baltimore has likely experienced the most active deforestation and forest succession across public and private land during recent decades (Zhou et al., 2011; Bowers et al., 2020).

Table 1
City information and forest patch characteristics for New York, NY; Philadelphia, PA; and Baltimore, MD. Forest patch area, number of forest patches, and forest edge to core ratio are summarized citywide and by patch type (forested natural areas (FNAs) and groves).

	New York City	Philadelphia	Baltimore
Land area (ha)	78,465	35,119	20,953
2020 population (US Census, 2021)	8,804,194	1,603,797	585,708
Percent total UTC cover (year assessed)	22 % (2017)	20 % (2018)	29 % (2018)
Percent forest patch cover citywide	3.9 %	6.3 %	8.3 %
Population density (people/ha)	112.2	45.7	28.0
Total forest patch area (ha)	3050.3	2202.4	1729.8
FNA area (ha)	2435.6	1880.8	1414.7
Grove area (ha)	614.7	321.6	315.1
Forest patch area / resident (m^2/person)	3.5	13.7	29.5
Number of forest patches citywide	3686	2032	1783
Number of FNAs	713	558	372
Number of groves	2973	1474	1411
Citywide forest patch edge to core ratio	1.18	1.18	1.06
Citywide FNA edge to core ratio	0.83	0.92	0.76
Citywide grove edge to core ratio	8.17	8.16	8.37

2.2. *Forest patch mapping*

In this manuscript we define forest patches as areas of contiguous tree canopy with naturally regenerating understory vegetation (i.e., no impervious surface or maintained lawn) that exist across a variety of ownership, land use history, and management practices (Fig. 2, Table S1). In addition, we separate forest patches into two categories, forested natural areas (FNAs) and groves, based on the amount of interior or core forest (see below). As with any landcover mapping exercise based on remotely sensed data, we cannot be certain what is on the ground (or underneath the canopy) at every location, but have developed a method of mapping urban forest patches that uses readily available data and is based on empirical field observations (see description below; Baker et al., in press).

Each city's forest patch map was created using existing high-resolution urban tree canopy (UTC) maps derived from Light Detection and Ranging (LiDAR) and National Agriculture Imagery Program (NAIP) imagery (City of New York, 2017; City of Philadelphia, 2018; Institute of Ecosystem Studies & O'Neil-Dunne, 2017). The UTC maps for Philadelphia and Baltimore had a spatial resolution of 1 m, while the NYC UTC map had a 6-inch (.1524 m) resolution. Because this forest patch mapping method begins with UTC as the input, it only includes the portions of forest covered by contiguous tree canopy. Operationally, natural areas can include sites managed as forest with vegetation below the minimum height of UTC (<2.44 m) and that do not appear in canopy maps, including large canopy gaps ($\gtrapprox$10 m^2) and early successional forest (Fig. 1; MacFaden et al., 2012).

To distinguish forest canopy cover from UTC, tree canopy over impervious surfaces was first subtracted from the canopy layer, including buildings and roads identified from open source planimetric data available from each city (City of New York, 2022; City of Philadelphia, 2025; City of Baltimore, 2025). 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 overstory and understory vegetation composition and structure derived from field-collected data (Baker et al., in press). MSPA applies the edge parameter to distinguish interiors (i.e. 'cores') from interior ('perforations') and surrounding edges, as well as four other morphometric primitives (i.e., branches, bridges, loops, 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). This use of MSPA with a 15 m edge width eliminated tree canopy made up of MSPA classes too small to contain core.

Resulting patches were separated into larger forested natural areas (FNAs) and smaller groves. FNAs were required to have a minimum core thickness greater than 22.6 m (defined as shortest distance across the thickest part of the core), whereas groves did not meet this requirement (Fig. 3). Thus, groves are smaller patches of tree canopy with less substantial core area (see Table S2 for range of FNA and grove patch sizes for each city). The minimum core thickness of 22.6 m for FNAs was initially selected to allow for field sampling of interior forest conditions using standard 0.1-acre fixed-radius plot protocols (Nowak 2020). Ground-truthing of 20 % of the FNAs in Baltimore has subsequently shown that all mapped FNAs are in a forested condition on the ground (i.e., minimal understory management, decomposition, natural regeneration; Sonti & Baker, unpublished data). We have intentionally included groves in this analysis in order to be inclusive of small patches of canopy that are likely to be natural areas. Ground-truthing of 10 % of the groves in Baltimore demonstrated that over 60 % have qualities of natural forested ecosystems (i.e., minimal understory management, decomposition, natural regeneration; Sonti & Baker, unpublished data), although some of these were found to have features underneath the canopy (e.g., streams) that were not visible from above. Other groves were found to have managed vegetation (e.g., lawn) in the understory.

Fig. 2. Photographs illustrating urban forest patches on the ground. (a), (b), and (c) depict municipal parkland in New York, NY; (d), (e), and (f) depict community-managed forest patches in Baltimore, Maryland, US. These sites contain FNAs or combinations of FNAs and groves. Photo credits: Rich Hallett (a, b, c); Nancy Sonti (d), and Eric Fishel (e, f).

2.3. Land ownership classification

Parcel data from each municipality was used to assign an ownership class to each parcel containing forest patches. Boundaries of ownership classes were snapped to match forest patch pixel boundaries when needed. Ownership categories include: Federal, State, Municipal, Commercial/Industrial, Institutional, and Private Residential ownership. Within parcel datasets, building type and owner name fields were most frequently used to determine ownership category and Google Maps imagery was used to provide additional information in challenging cases. Local experts in each city were consulted about errors or gaps in the parcel data and supplementary datasets were used (e.g., Integrated Property Information System (IPIS) public lands database in NYC). Institutional properties included private schools, universities, religious properties, medical centers, hospitals, community centers, veterans administrations, cemeteries, foreign-owned properties, museums, non-profits, psychiatric centers, and boy scouts properties. Condominiums, apartment complexes, and other large multi-unit residential structures were categorized as commercial ownership, reflecting our analysis of land ownership (commercial) rather than land use (residential). Properties under the names of individual people were generally classified as private residential ownership, unless contradicted by imagery and other sources of information. Parcels with unknown ownership were investigated using Google Maps imagery and were generally assigned municipal ownership (e.g., public rights of way), except for property associated with state or interstate transportation corridors, which was classified as state ownership. Forest patches often cross parcel boundaries, so one patch may have multiple owners and ownership classes.

2.4. Data Summaries and analysis

For each patch, we calculated (1) the ratio of forest edge area to core area, (2) patch size, (3) patch thickness, (4) patch shape index, (5) number of individual property parcels, and (6) number of owner types. Results of MSPA provided class segmentation of canopy pixels, which were given unique identification numbers by applying the *regiongroup* function to all core pixels and expanding those assignments to edge/perforation pixels using a *costallocation* function within ArcGIS (ESRI, Inc). Area for each class was thus summarized using a *tabulatearea* function for each patch as a distinct zone. Forest patch thickness was defined as the shortest distance across the thickest part of the patch determined using twice the zonal maximum of a *costdistance* function over canopy pixels from patch edges towards interiors. Shape index, a measure of compactness defined as $\text{Perimeter}^2 * (4 * \text{pi} * \text{Area})^{-1}$ where a circle has a minimum shape index value of 1, was obtained by relating areal estimates to patch perimeters obtain through *zonalgeometry* function. Number of individual property parcels per patch were assessed using the parcel data described above and number of owner types per patch was assessed using the ownership classification described above, assessed as 1-m rasters within each patch using a *zonalcount* function. We also calculated the total area and ratio of edge to core area of contiguous areas of ownership within each forest patch using *tabulatearea*. We then summarized citywide distribution of forest patch

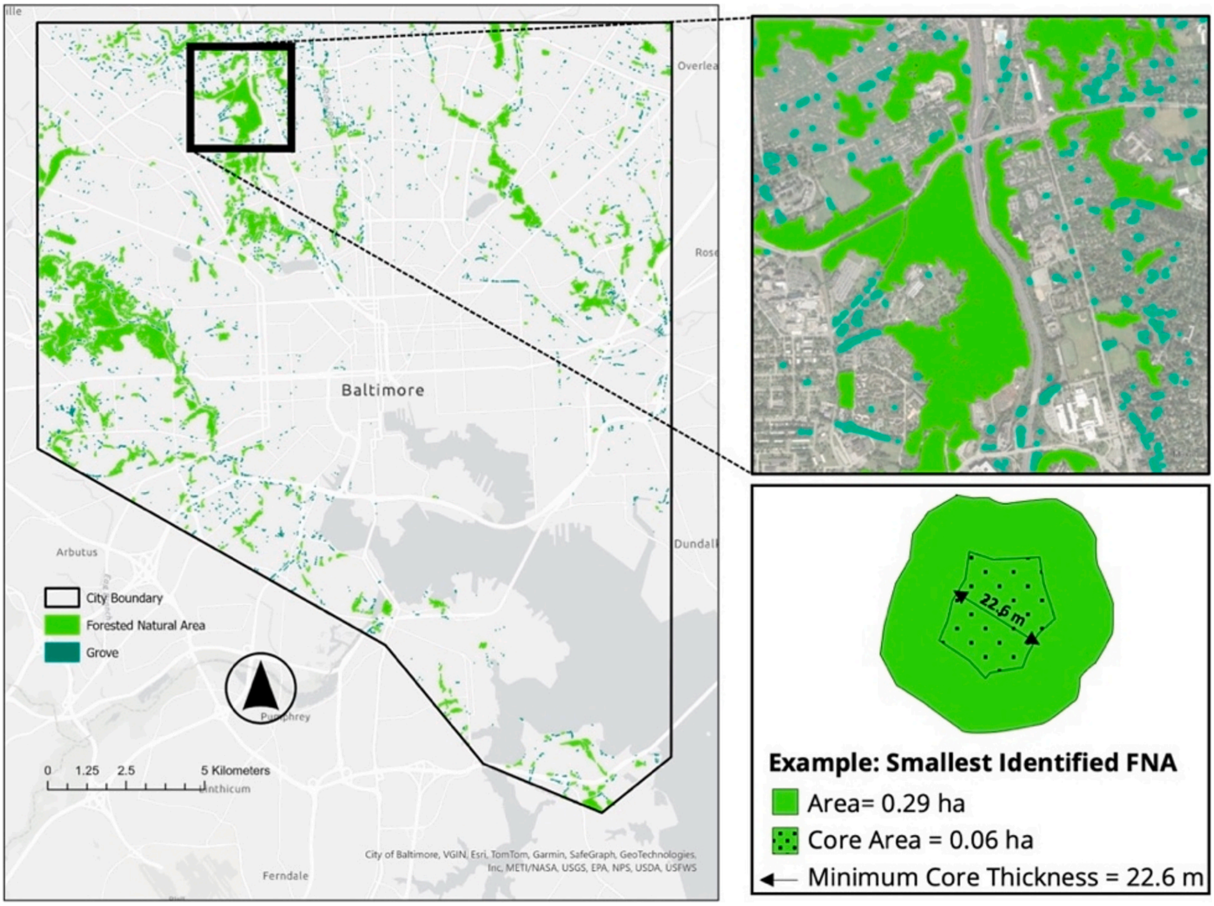

Fig. 3. Citywide forest patch map for Baltimore, Maryland, USA with inset depicting forested natural areas (FNAs) and groves. Many of Baltimore's large forested natural areas are located along stream valleys. Diagram illustrates minimum FNA dimensions.

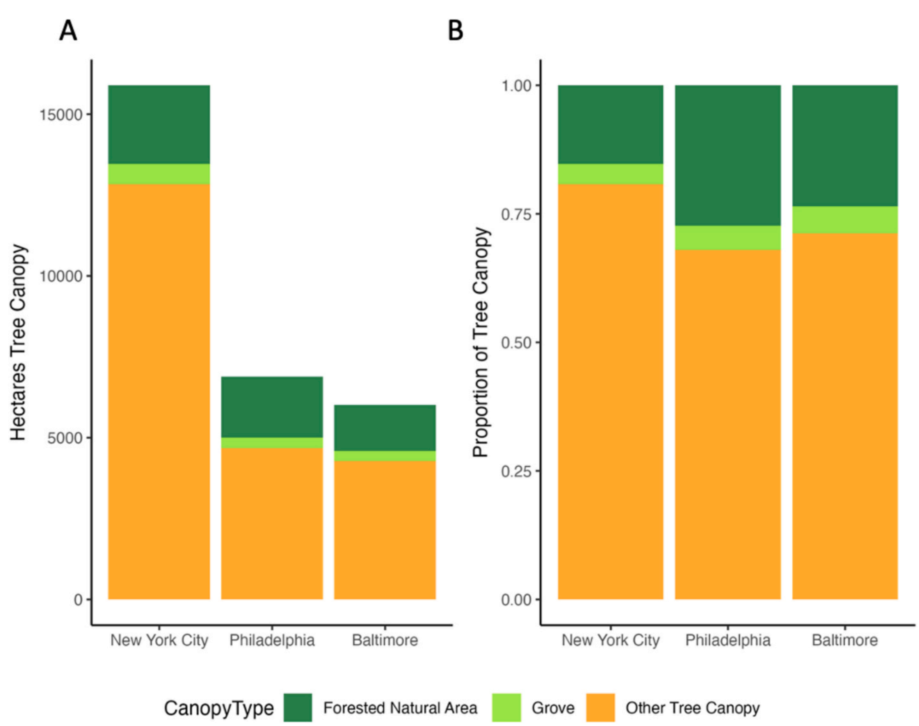

Fig. 4. Total urban tree canopy (UTC) cover by city and forest patch type (forested natural area or grove). (A) Hectares of tree canopy by forest patch type or other (non-forest) tree canopy across the three cities. (B) Proportion of tree canopy by type across the three cities.

numbers, area, and characteristics by city and by ownership class within each city. Kruskal-Wallis tests were used to compare social and ecological forest patch characteristics by city within each patch type (forested natural area or grove) or among ownership classes within each city and patch type.

3. Results

3.1. Patch characteristics

Across the three cities, there was variation in the amount and proportion of forest canopy cover, inclusive of both FNAs and groves (Fig. 4, Table S2). Baltimore had the greatest citywide percent forest canopy cover at 8.3 % of the city's land, which made up 29 % of total UTC, while Philadelphia had 6.3 % forest canopy cover making up 32 % of total UTC, and NYC had 3.9 % forest canopy cover making up 19 % of total UTC (Table 1). Among the three cities, Philadelphia has the greatest proportion of total UTC in FNAs (27 %) while Baltimore has the greatest proportion of total UTC in groves (5 %; Fig. 4). Baltimore has the greatest forest patch area per resident (29.5 m^2/person) followed by Philadelphia (13.7 m^2/person) and NYC (3.5 m^2/person) (Table 1).

With the largest land area by far, NYC has the greatest total forest patch area citywide, including the greatest area of both forested natural areas and groves (Table 1). While Philadelphia has a greater number and area of FNAs than Baltimore, Baltimore has a similar amount of groves as Philadelphia (both in number and land area), despite being about 60 % as large as Philadelphia. Groves make up a similar proportion of total forest patch area across the three cities, ranging from 20 % of NYC forest patch area, to 18 % in Baltimore, and 15 % in Philadelphia (Table 1). New York City and Philadelphia have higher citywide forest patch edge to core ratios than Baltimore, suggesting that, overall, these cities' forests are more fragmented (Table 1). Baltimore's FNAs have a lower citywide edge to core ratio than the other cities, whereas Baltimore's groves have a higher edge to core ratio than the other two cities.

Median FNA size is greater in Baltimore than in NYC, with Philadelphia falling in between (Fig. 5a, Table S2). Groves are significantly larger in Baltimore than in Philadelphia but the difference in median grove size is only 0.01 ha (Fig. 5b, Table S2). Fig. 5a and 5b depict the distribution of forest patch sizes, with large outliers in each city removed for display purposes. Examining the ranges of patch sizes, NYC has the largest individual FNA by far (130 ha), 1.3 times larger than Baltimore's largest FNA and 2.6 times larger than Philadelphia's largest FNA (Table S2). Baltimore has the largest individual grove (1.82 ha), but there is generally less variation in grove size among cities because the size of groves is constrained to a relatively narrow range (Table S2).

Median FNA and grove thickness are greater in Baltimore than in Philadelphia and NYC (Fig. 5c,5d; Table S2). Despite these statistically significant differences in median patch thickness between cities, the magnitude of differences is small (4 m or less; Table S2). New York City and Philadelphia median FNA shape index values are significantly lower than Baltimore (Fig. 5e). All three cities have significantly different median grove shape index values, with Philadelphia's being the highest and thus the most elongated (Fig. 5f).

3.2. Patch ownership

Baltimore has the largest median number of individual property parcels per forest patch (both FNAs and groves), significantly higher than the other two cities (Fig. 6; Table S2). Baltimore also has significantly more owner types per FNA (Fig. 7; Table S2). Only 25 % and 50 % of Baltimore's FNAs and groves, respectively, have one owner type per patch, which is a lower proportion than in the other two cities (Fig. 7).

All three cities have more municipally owned forest (FNA and grove area) than any other individual ownership type (Fig. 8). However, NYC has a much greater amount and proportion of FNA and grove area on state and federal land compared to Philadelphia and Baltimore. Citywide, Baltimore has the greatest proportion of FNA and grove area on privately owned land, while NYC has the smallest proportion on private land ownership types (Fig. 8). About 32 % of Baltimore FNA cover is privately owned compared to 17 % and 13 % in Philadelphia and NYC, respectively. This pattern is even more pronounced for groves, where 61 % of Baltimore's area of groves are found on privately owned land compared to 36 % and 22 % in Philadelphia and NYC, respectively.

Forest patch characteristics by ownership class follow similar patterns. Looking at contiguous areas of ownership within patches, Baltimore and Philadelphia have a larger median commercial/industrial and private residential patch areas within FNAs compared to NYC (Table S2, Fig. S1). In NYC and Philadelphia, publicly owned FNA patches are generally larger than those on privately owned land, with private residential FNA patches having the smallest median size. There are fewer significant differences in median patch size of FNAs by ownership in Baltimore, where institutional FNA patches have the largest median area along with municipal ownership. Overall, there are fewer significant differences in median patch size of groves by ownership class, given the constraints on the size of groves. However, private residential groves are among the smallest in each city and federally owned groves are among the largest.

Variation in forest edge to core ratio among ownership types tends to mirror overall patterns of median patch size (Table S). For example, Baltimore's FNAs have less variation in median patch size and less variation in edge:core forest among ownership types. Looking across cities, Baltimore has the lowest FNA edge to core ratio on private residential land and also the largest median FNA size on private residential land by far. However, the ranking of edge:core forest among ownerships within each city does not always mirror median patch size. For example, FNAs on commercial/industrial land in NYC rank lower in edge:core forest among the city's ownership types than might be expected given their relatively small median size. This is likely due to large outliers which have a greater impact on the citywide core fraction of each ownership class than on median patch size. Forest edge to core ratio is less variable among grove ownership classes, with the exception of state and federally owned groves, which have the smallest and largest values. However, with very little total area of state or federally owned groves, these edge:core values represent a small amount of forest canopy cover.

4. Discussion

Delineation and disambiguation of forest patches from other types of urban tree canopy revealed important differences in spatial characteristics and ownership of forest patches across the three cities. These differences have implications for forest conservation and management, and for delivery of social and biophysical ecosystem services to urban neighborhoods.

4.1. Forest patch distribution and characteristics

As the largest and most densely developed city, NYC has the lowest percent forest canopy cover citywide, whereas Baltimore has the greatest percent forest canopy cover and Philadelphia falls in between. Baltimore's FNAs have the lowest edge to core ratio among the three cities, which can be explained by their larger size and greater thickness, despite being less round (higher shape index) than FNAs of the other two cities. Large forest patches with a low ratio of edge to core forest can provide unique opportunities for biodiversity in an urban setting (Kang et al., 2015; Doroski et al., 2022) and may experience less human disturbance, with fewer edge effects such as invasive species introduction or illegal dumping in areas of interior forest. The largest forested areas in all three cities are municipally-owned public parkland highlighting the importance of public land protection and management in cities (Lawson & Plitt, 2023). The location of these large natural areas may impact their proximity to local populations, which is an important factor for urban natural area visitation (Sonti et al., 2020). For example,

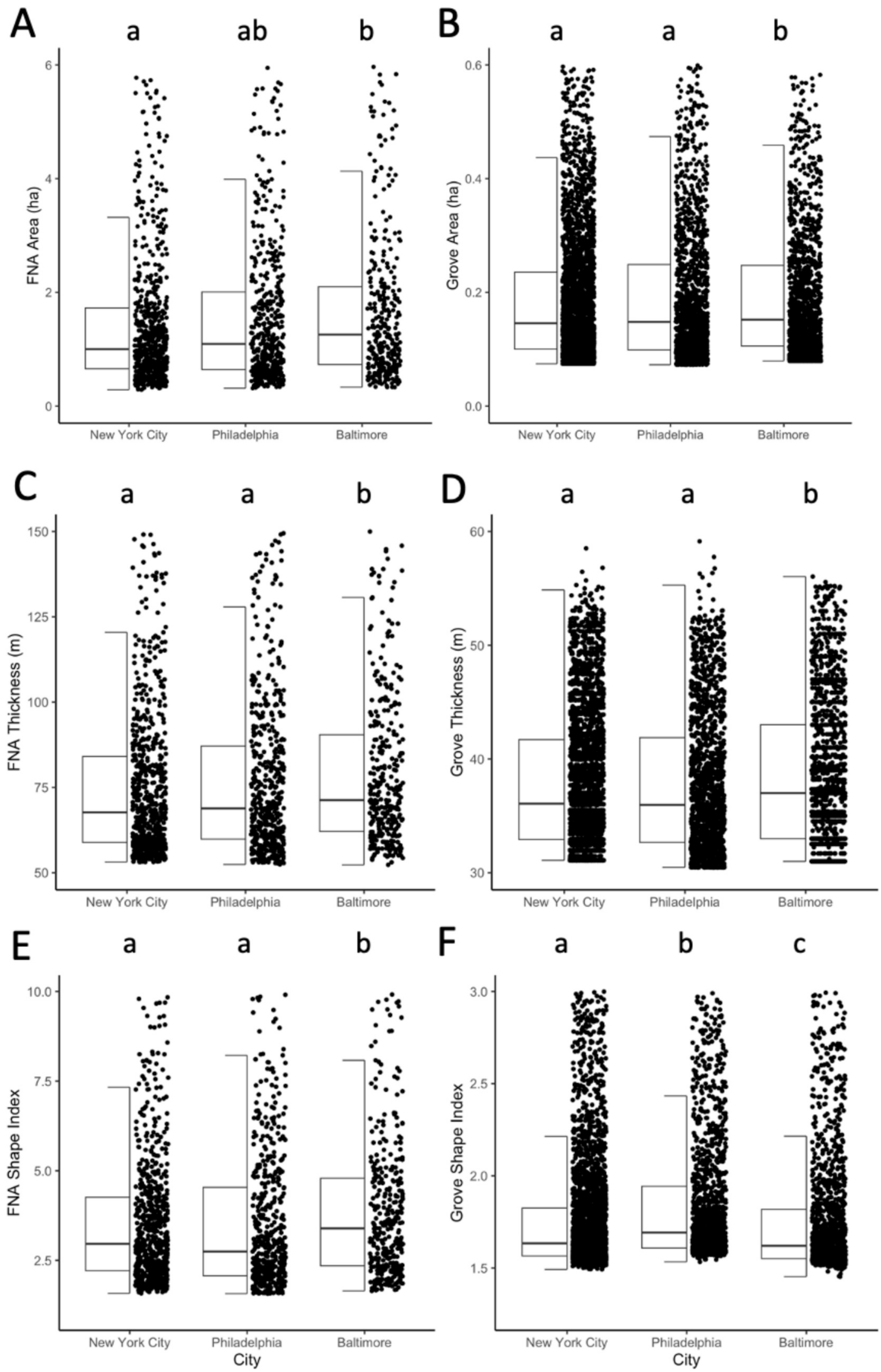

Fig. 5. Forest patch structure by city and forest patch type. Box plots depict median and interquartile range with outliers removed. Letters represent significant differences in forested natural area (FNA) or grove metrics by city using Kruskal-Wallis test with pairwise comparisons. Alpha = 0.05 for pairwise comparisons with the exception of median patch size of FNAs where Kruskal-Wallis test p = 0.04 and p = 0.058 for pairwise comparisons. Numbers of FNAs and groves used in these analyses can be found in Table 1. (A) median FNA area, (B) median grove area, (C) FNA thickness, (D) grove thickness, (E) FNA shape index, and (F) grove shape index.

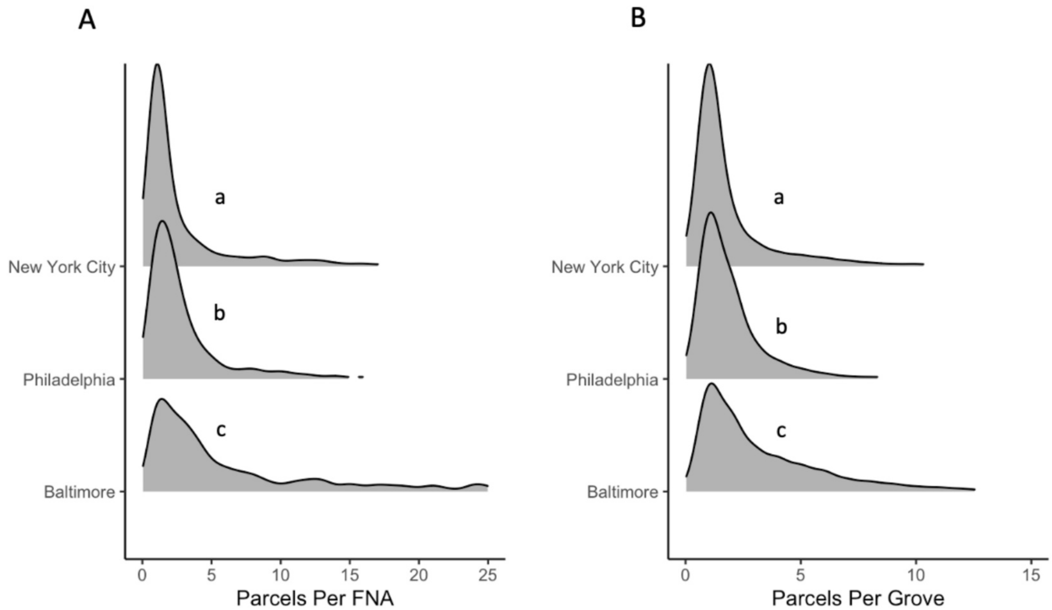

Fig. 6. Number of property parcels per FNA (A) and per grove (B) in New York, NY; Philadelphia, PA; and Baltimore MD. Letters represent significant differences among cities using Kruskal-Wallis test with pairwise comparisons ($p < 0.05$).

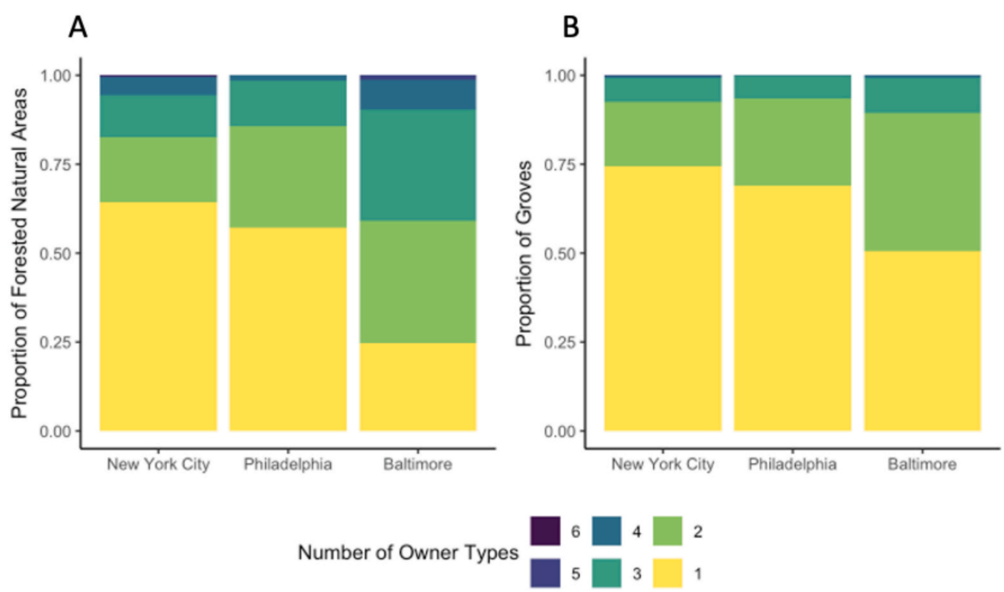

Fig. 7. Proportion of forested natural areas (FNAs) (A) and groves (B) by city and number of owner types.

large forests on the edge of the urban core may be difficult to reach by public transportation and, as a result, may be less frequently visited by residents from other neighborhoods. In addition, considering social factors alongside spatial proximity is critical to understanding the conditions that may facilitate or dissuade residents from using urban natural areas (Weiss et al., 2011). More research is needed on forest patch visitation rates across different land ownerships, patch configurations, and neighborhood demographics.

Groves are more constrained, by definition, and show fewer differences in structure across cities, but are significantly larger and thicker in Baltimore, despite having a higher edge to core ratio than in the other cities. Although groves cover a much smaller total area of each city than FNAs, they may provide important sites of nearby nature to urban residents when they are isolated from other green spaces in the urban landscape. Fragmentation of forest canopy cover results in greater amounts of edge forest, which may not provide the same ecological function or native species habitat as interior forest (Franklin et al., 2021; Meeussen et al., 2021). However, more fragmentation can result in a wider geographical distribution of ecological benefits to surrounding neighborhoods, such as stormwater interception (Carlyle-Moses et al., 2020), urban heat island mitigation (Alonzo et al., 2021), or wildlife viewing (Soulsbury & White 2015; Sonti 2020). Smaller FNAs and groves may be in closer proximity to residents if they are embedded in the community landscape, particularly when they are community-managed open spaces (Morzillo et al., 2022). In addition, isolated forest patches may experience less deer pressure and greater native seedling regeneration than larger forested habitat corridors (Jenkins & Howard 2021). For these reasons, it is socially and ecologically important to have both large and small forest patches in a city.

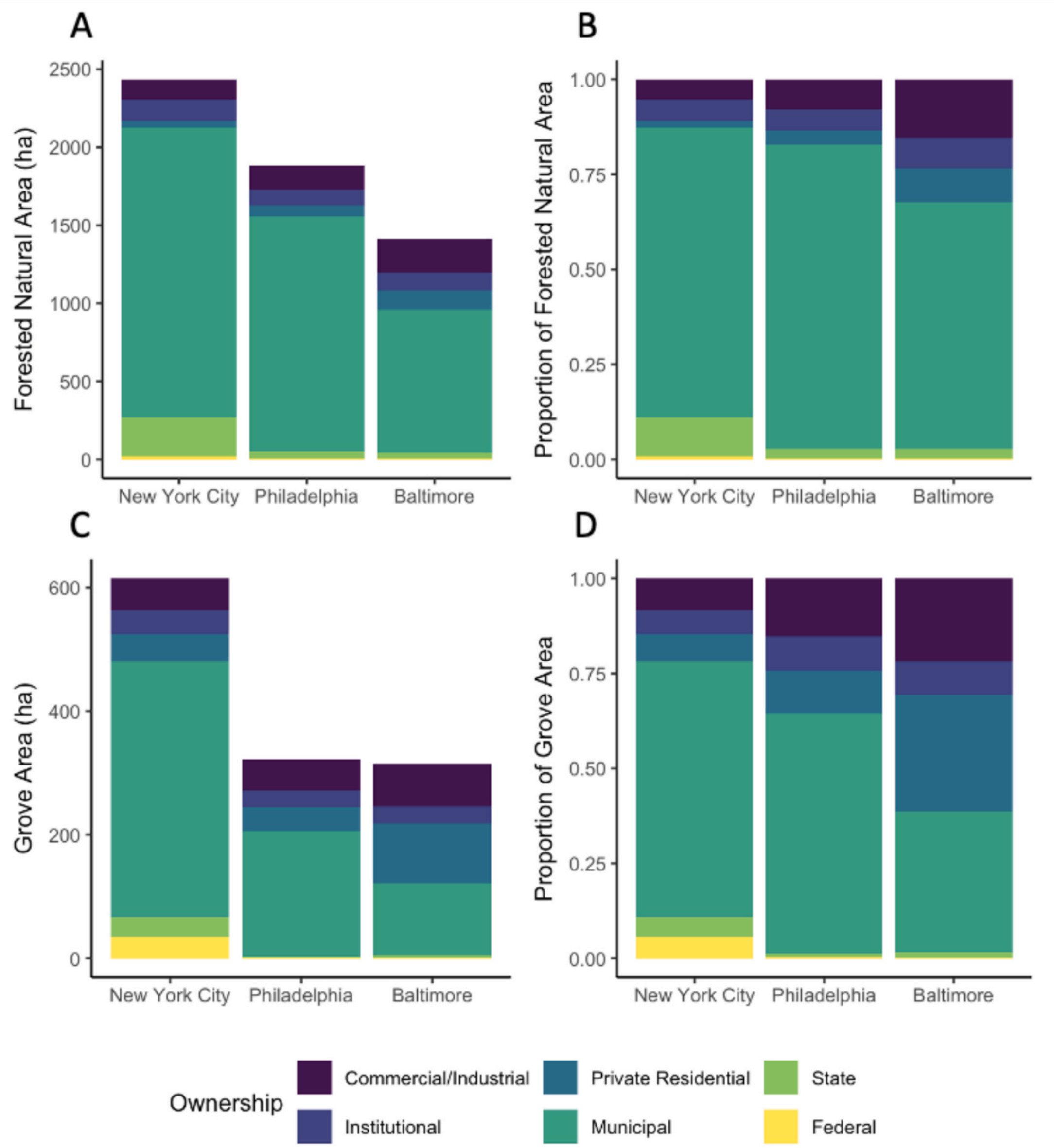

Fig. 8. Citywide forest patch area by city and ownership class. (A) area (ha) of forested natural areas (FNAs) by ownership class; (B) proportion of FNA area by ownership class; (C) area of groves by ownership class; (D) proportion of grove area by ownership class.

4.2. Physiographic constraints and land use planning Legacies

Modern distribution of forests in these cities is driven in part by landscape physiography, as well as the legacy of planning and development decisions (Roman et al., 2018). Landform and topography have limited development on some of the largest protected open spaces in each city. Baltimore and Philadelphia's largest municipal parks are found along stream valleys running north–south through each city, though Baltimore's stream valley parks are more irregularly shaped and proceed farther into the city center than in Philadelphia (Figs. 1, S2). This may explain our finding that FNAs and groves are more rectilinear in Baltimore than in Philadelphia and NYC. The steep slopes leading down to these waterways have shallow soils unsuitable for agriculture or urban development, and so have remained forested over time (Sonti et al., 2024). Rather than stream valleys, NYC has both rock outcrops and low-lying coastal areas that are not suitable for urban development and now support large areas of adjacent forest. For example, several NYC parks located in Queens are situated on the terminal moraine of the Wisconsin glaciation, and other forested natural areas such as those in Inwood Hill Park in Manhattan are located on metamorphic rock formations.

Overlaying these geophysical drivers of land use are distinct histories of population growth and loss, and associated periods of economic development and open space protection and maintenance over time in each city. Incorporation of historical land cover data into analysis of urban forest patch conditions has revealed that the disturbance history of forest patches impacts present-day composition and structure. For example, forest patches with a more recent history of development or agricultural use have lower average tree canopy heights (Sonti et al., 2024), have higher abundance of invasive plant species (Pregitzer & Bradford, 2023), and are more fragmented (Darling et al., 2025). Furthermore, different classes of forest patch history are not uniformly distributed across present-day land ownerships or in relation to present-day urban populations, leading to varying patterns of forest age and quality across neighborhoods and land uses (Sonti et al., 2024; Darling et al., 2025).

Our analysis highlights the legacy of economic development patterns across forest ownership classes within the three cities. Baltimore's large amount of vacant and undeveloped land may contribute to the city having more forest on private land spanning multiple smaller parcels (Avins, 2015). As expected, NYC's forest is largely on public land where it may be protected from the intense development pressures found in the nation's largest city. However, it is important to note that public ownership does not necessarily equal protection from development or conversion to other land uses (Bowers et al. 2020). It is also important to note that not all publicly-owned land is parkland available for public use. Many different municipal agencies may own forested land, which may or may not be open for recreation. Similarly, while some privately-owned forest land may be closed to the public, there are institutional forest lands open to the public and community-managed forest patches on privately-owned land that are available to community residents (Morzillo et al., 2022).

New York City has a much greater amount and proportion of forest canopy cover on state and federal land compared to Philadelphia and Baltimore. Some of this land is part of the Gateway National Recreation Area, which extends across parts of coastal Brooklyn, Queens and Staten Island. Over 13,000 acres of city parkland were transferred to the National Park Service for the creation of this national park in 1974 (City of New York, 2024). Clay Pit Ponds State Park was created in 1977 and also contains significant forest canopy cover. Although Baltimore and Philadelphia have federally-owned protected areas as well, these are more wetland focused (e.g., Masonville Cove Urban Wildlife Refuge in Baltimore, John Heinz National Wildlife Refuge in Philadelphia). As a result, there is a greater opportunity to coordinate among municipal, state, and federal government agencies about inventory, monitoring, and management of forested areas in NYC than in the other locations.

All three cities have large municipal parks with substantial forest cover established from the mid-nineteenth century into the early twentieth century. The legacy of these early planning efforts is apparent in the large amount of municipally-owned forest present in each city today. However, historical research has shown that these properties are not static. All three cities experienced periods of depopulation, economic decline, and associated municipal staffing and budget cuts during the second half of the twentieth century. Philadelphia's agency charged with the management of municipal forested areas was continually underfunded since its establishment, and forest canopy cover was documented to have expanded on Philadelphia city parkland during periods of acute economic decline in the 1960s and 1970s (Nix et al., 2023). A similar phenomenon is likely to have occurred to varying degrees in the other cities. In the 1980s, the NYC Department of Parks & Recreation established the Natural Resources Group and began to inventory thousands of acres of "undeveloped" lands under the agency's jurisdiction (Cullman et al., 2023). Since that time, the Natural Resources Group has steadily increased its knowledge and expertise in managing forests in cities, becoming a resource for other cities and organizations who want to assess and manage urban natural areas (NYC Parks, 2014).

4.3. Conservation and management implications of forest patch ownership

Physiographic constraints helped shape early settlement, subsequent industrial development, and open space conservation in each of the cities included in this analysis. These historical processes contributed to present-day land tenure, which has important implications for the conservation and planning strategies required to effectively manage forests in cities (Lawson & Plitt, 2023). Areas of contiguous municipal ownership within forest patches have some of the largest median values across FNAs and groves of all three cities, while areas of contiguous private residential ownership have the smallest median values. Municipal ownership also typically has among the lowest citywide edge:core values, while private residential ownership has among the largest citywide edge:core values across FNAs and groves of all three cities. Areas of commercial/industrial and institutional forest ownership present a compelling opportunity for further conservation and management, given that they have intermediate median sizes, and occupy substantial portions of forest canopy cover in each city.

Baltimore has the largest number of property parcels per patch for both FNAs and groves, and the largest number of owner types per FNA compared to the other two cities. Baltimore also has the greatest amount of privately owned forest cover, followed by Philadelphia and then NYC. The comparatively large amount of privately-owned forest found in Baltimore, particularly on commercial/industrial and private residential lands, may experience less cohesive management than larger parcels of public or institutional lands (Aronson et al., 2017). In addition, unmanaged and undeveloped private land in cities with high vacancy rates like Baltimore may be owned by deceased or economically challenged individuals, making the land eligible for foreclosure (Scott & Iyer, 2020). However, without local development pressure, these properties may remain in a sort of "limbo" where the city holds a lien on the property until tax payments are made (Jacobson, 2014). Such liens may effectively function as conservation easements, providing unintended protection from development until foreclosure or another type of property transfer takes place. Future research could investigate the spatial and temporal extent of liens placed on forest patch properties in order to gain a better understanding of the importance of this process in influencing the dynamics of forest cover in each city.

Detailed information about the number and type of land owners helps clarify who has legal decision-making power over a particular forest patch and who makes management decisions on the ground. This information also makes it easier to protect forest patches by acquisition into a land trust or into a public park system and to understand how public advocacy might help influence this process (Avins, 2015). Coordinating across multiple owners and different types of owners to preserve or sustainably manage contiguous areas of forest canopy may be more complex. Forest patches with fewer property owners are logistically easier to transfer, with fewer individual parties to coordinate and less paperwork (deeds, easements, etc). Implementation and coordination of regional conservation initiatives may be more complicated when there are diffuse patterns of forest patch cover and varied land ownership (Newburn et al., 2005; Campbell, 2009). In the absence of coordinated mapping and dissemination, local land trusts and conservation organizations are often left to do the hard work of in-house research on individual property parcels to find out ownership and legal status of forest patches suitable for protection, or they may use valuable resources to hire consultants or use data from regional conservancies and larger land trusts (Land Trust Alliance, 2020). The forest patch maps presented in this paper do not provide all of the property information needed for conservation action, but rather, are a starting point that allows for strategic citywide or regional conservation planning (Gerber & Rissman, 2012; Bargelt et al., 2020). To this end, the forest patch maps used in this analysis are available to view and download in an ArcGIS Online application (Sonti & Baker, 2023).

The information presented here may also be paired with field inventory data to prioritize conservation and management actions. Forest vegetation inventories from each city have shown that urban forest patches are dominated by native canopy trees, but are threatened by invasive vines, shrubs, and herbaceous plants in the understory (Pregitzer et al., 2019; Trammell et al., 2020; Baker et al., 2025). Thus, active forest management is critical to ensuring future native canopy and associated ecosystem services. Maps of forest patches by size and ownership class can be used to target future field inventories in order to better understand patterns of forest vegetation and soil structure and diversity across these categories, and to direct subsequent conservation efforts.

The unique historical contexts, financial resources, and present-day geography of forest ownership have led to different areas of focus for conservation and management in each city. The NYC-based non-profit Natural Areas Conservancy was founded in 2012, adding local scientific capacity and new sources of funding for inventory and management of

NYC's forested parkland. The Natural Areas Conservancy has also founded a national network supporting the science and management of Forests in Cities, building upon the extensive knowledge of NYC's Natural Resources Group. While Philadelphia's Fairmount Parks Conservancy has done similarly innovative work managing the city's natural lands, they have operated with a much smaller staff and budget. Both Baltimore and Philadelphia have experienced sporadic efforts to inventory individual forested parks over the past several decades, with both cities currently embarking on more systematic efforts to inventory all municipal forest lands and create management plans for each property (City of Philadelphia, 2023). Since 2011, non-profit Baltimore Green Space has also been a pioneer in advocacy and science-based management of community managed forests, releasing their first white paper about Baltimore's Forest Patches in 2013 (Avins, 2013). The organization has led inventories of forest patches across all ownership categories, a dataset which is unique to Baltimore among these cities. The Natural Areas Conservancy and Baltimore Green Space are national advocates for urban forest patches, bringing their unique local perspectives and knowledge to national and international conversations about urban greening.

Forest patch area per resident has an inverse relationship with population density across the three cities, increasing from NYC to Philadelphia to Baltimore. Baltimore is the smallest and least densely developed city, and has the greatest percent tree canopy cover and percent forest canopy cover. This also results in the greatest amount of forest canopy cover per resident, which at 29.5 m^2/person is almost ten times that of NYC. More research is needed to understand whether this pattern extends to other "shrinking cities" experiencing depopulation, and what the implications might be for conservation in the local social, economic, and ecological contexts of these urban areas. More analysis is also needed to understand the distribution of forest canopy cover in relation to human populations in each of the cities studied here. For example, Darling et al. (2025) found that communities of color in Chicago are less proximate to forest overall, but especially to forests with the capacity to provide greater regulating and provisioning ecosystem services. However, it is important to understand both physical distance and perceptions of access within urban communities (Weiss et al., 2011). Urban forest patches can elicit strong positive and negative feelings from community residents, depending on personal and local context (Sonti, 2020). Recent planning goals like the "3-30-300 green space rule" are important initiatives to enhance urban quality of life (Konijnendijk, 2022). However, the quality of urban tree canopy or green space, and accessibility of those amenities is also important to consider.

4.4. Limitations to mapping forest patches from UTC

Our forest patch mapping method was developed to be widely replicable with publicly available datasets and straightforward spatial analysis methods. However, it is important to note that in the absence of an accurate parcel ownership database, assigning ownership to forest patches may be time consuming and labor intensive. Tree canopy cover goals are increasingly embedded in urban forest management and planning, particularly in the United States and Canada, making these data widely available (Roman et al., 2021). Planimetric datasets are also generally available for municipalities, and the MSPA method is straightforward and widely used. Differences in UTC spatial resolution may affect comparability between cities or comparisons of forest patch extent over time. In our analysis, the NYC UTC data had a resolution of 6 in. (0.15 m) while the other cities had 1-meter resolution UTC. This will lead to marginally more precise measures of distance in NYC, but the scale of the pixels in the UTC layers is small relative to the size of the objects we were mapping (trees within forests). The distortion inherent in aerial imagery is likely to contribute an equivalent or greater amount of error compared to the differences in such high-resolution datasets.

One constraint of this forest patch mapping method is that it only includes tree canopy cover. Forested areas include canopy gaps as well as early successional areas, which may be extensive in urban settings with frequent human disturbances, land abandonment, and recent mortality events from pests and pathogens (e.g., widespread ash tree mortality from emerald ash borer). These gaps and early successional areas are more difficult to map, although it is possible to do so with substantial resources and many manual corrections (O'Neil-Dunne et al., 2014; CBPO, 2022). Our approach is automated, and easy to replicate across urban areas with a few data source inputs. While it identifies places likely to be forest, it may not capture the entire area being managed as a "forest" within a given city. Public agencies sometimes have more extensive maps delineating these areas, though such maps are usually confined to parkland, rather than all public lands and the extent of forest cover on private lands is generally unknown in urban areas.

Another limitation of our method is that some groves may not qualify as forest patches on the ground. Our ground truthing in Baltimore has shown that substantially more than half of groves are forest patches with natural regeneration processes occurring on the forest floor. However, some groves have mown grass or other highly managed vegetation, and others may have features that reduce their area (e.g., stream or paved pathway) below the threshold for a forest patch. We have chosen to be more inclusive with our definition so that we capture the majority of groves that are in fact forest patches on the ground. Our method provides a way to identify potential forest patches, particularly on private lands and on public lands where they are not actively managed or protected as natural areas. Furthermore, because our method is relatively rapid, there is a greater ability to repeat the analysis with subsequent urban tree canopy maps and track canopy change across ownerships over time.

5. Conclusions

Although forest patch canopy typically covers a small fraction of a city's land area, it can deliver disproportionately greater ecosystem services to urban populations compared to other types of green space (Mexia et al., 2018), including stormwater capture (Phillips et al. 2019), urban heat island mitigation (Alonzo et al. 2021), and opportunities for nature experiences (Sonti et al. 2020). The amount and configuration of urban forest patches will help determine the social and ecological functions that they provide, contributing to climate resilience, biodiversity, wildlife habitat, and human health and well-being at neighborhood and citywide scales. In this analysis, we distinguished patches of forest from other tree canopy types using high resolution urban tree canopy maps and planimetric data from three major cities of the eastern U.S., and compared forest patch spatial characteristics and ownership across the three cities. While all cities have a majority of forest patch area located on municipal property, Baltimore has the greatest amount of privately owned forest and also has the largest number of property parcels and owner types per patch compared to the other two cities. Baltimore's forest also has the largest median patch sizes, and the lowest citywide forest edge to core ratio. As the most densely populated city, NYC has the lowest citywide forest patch cover and forest patch area per resident. The distribution of forested areas in cities is a result of biogeographical constraints along with historical economic development patterns and management priorities over time (Jorgensen & Keenan, 2012; Roman et al., 2018). More research is needed to refine our understanding of the ownership and distribution of forest patches and other types of urban natural areas throughout historical, cultural, and ecological contexts beyond the eastern U.S. These patterns have implications for present-day forest patch governance and stewardship (Ogden et al., 2018), and may be used to direct and coordinate effective approaches management and conservation across property boundaries with limited resources.

CRediT authorship contribution statement

Nancy F. Sonti: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Conceptualization. **Matthew E. Baker:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Michael Allman:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Richard A. Hallett:** Writing – review & editing, Validation, Conceptualization. **Michelle P. Katoski:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Katherine Lautar:** Writing – review & editing, Writing – original draft, Validation, Conceptualization. **Max R. Piana:** Writing – review & editing, Visualization, Validation, Conceptualization. **Clara C. Pregitzer:** Writing – review & editing, Validation, Conceptualization.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2025.105374.

Data availability

Data are available to view and download from the USDA Forest Service: https://experience.arcgis.com/experience/e9801ba79ba0487c8a027390da49fbea/

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