Urban Forestry & Urban Greening 107 (2025) 128778

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

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

Legacies of urbanization and suburbanization on forest patch distribution, ownership, and use: Insights from Baltimore, Maryland

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ARTICLE INFO

Keywords:
Chesapeake Bay
Baltimore
Forest patch
Natural area
Morphological spatial pattern analysis

ABSTRACT

Comprehensive high resolution land cover and parcel data provide new abilities to map and identify discrete forest patches across different ownerships and land uses, from urban to rural settings. Mapping of forest patches can inform forest management and protection, to maintain ecological benefits for diverse populations. We use parcel data in combination with high resolution land cover to map and characterize 20,146 unique forest patches covering 581.9 km^2 across urban Baltimore City and suburban and rural portions of Baltimore County. Typical of the eastern United States, initial urban development in this region gave rise to suburban expansion during the 20th century. We found size and number of forest patches, as well as the proportion of forest spanning multiple parcels, all increased when moving outward from urban to rural areas. The number of forest patches went from nearly 2000 in Baltimore City (9.7 % of land area) to 7700 forest patches within suburban Baltimore County, within the urban growth boundary (17.9 % of land area), to nearly 10,500 in the rural portion of Baltimore County (44.7 % of land area). However, ownership type and land use of forest patches, as derived from parcel data, was unique for each region: public ownership was more common within the city, and private ownership, with residential and agricultural land use, more common in suburban and rural Baltimore County, respectively. For all of the regions we considered, most of the forest area and the larger forest patches were distributed across numerous parcels and many types of ownership and land use. For each of these regions, working across parcel boundaries has the potential to expand forest conservation and management, but will involve a range of owners and land use types, including public parks, residential areas, and farmland, from urban to rural settings.

1. Introduction

Forest ecosystems in the United States offer pivotal social and ecological benefits across a range of landscapes. From densely developed urban areas to more rural settings where forest remains the dominant land cover, forests provide wildlife habitat, sequester carbon, filter water and offer flood control, while also creating recreation opportunities and benefiting human health and well-being (Binder et al. 2017; Cavender-Bares et al. 2022). However, forest cover is also the most dynamic land cover type in the United States, with forest frequently removed for development, during harvesting, and by natural disturbance (Homer et al. 2020). Given both the benefits of forests and their dynamic nature, it is critical to understand when and where forested areas and ecosystem processes are retained across a range of development intensities, from urban centers, suburban areas, and more rural settings (Riitters et al. 2020; Johnson et al. 2021; Sonti et al. 2024).

Examining forest across a gradient of urbanization typically finds that forest patches are smaller and more isolated in cities, but as areas become less developed and more rural, forest patches are larger, in closer proximity to one another, and cover more area (McDonnell and Hahs, 2008). Fragmentation and parcelization of forests result in increased presence of invasive species, increased pollution, and altered biogeochemical cycling, among other effects (Murcia, 1995; Hansen et al. 2005; Morreale et al. 2024). Differences in ownership and land use can further increase "management fragmentation", that is, reducing shared management goals and opportunities for collaboration between administrators (Aslan et al. 2021). Much of the literature on fragmented management and forest parcelization focuses on private lands, with an

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https://doi.org/10.1016/j.ufug.2025.128778
Received 4 September 2024; Received in revised form 10 March 2025; Accepted 11 March 2025
Available online 24 March 2025
1618-8667/Published by Elsevier GmbH.

emphasis on cross-boundary wildfire risk reduction or maintaining timber production (Hatcher et al. 2013; Charnley et al. 2020; Aslan et al. 2021). When forests are divided among many owners, particularly because of expanding development, it is challenging to coordinate production forestry, comprehensively manage forests to reduce wildfire risk, and/or even to maintain forest cover. Collaborative management is often seen as key after fragmentation, for increased technical assistance, better education and information about management options, and enhanced management opportunities as a result of economies of scale (Hatcher et al. 2013; Fischer et al. 2019).

Studies of forest cover across gradients have relied on moderate resolution (e.g., 30 m) imagery from LANDSAT and occurred in rural or exurban settings, imagery and locations that obscure the role of small forest patches and the variation in forest cover, ownership, and use that occur in more developed settings (Giner and Rogan, 2012; Huang et al. 2015). Increasingly, efforts to understand forested areas and ecosystem services are relying on high resolution (e.g., 1 m) imagery across entire landscapes (Pregitzer et al. 2019; Sonti et al. 2024). Using these forest data in combination with data for impervious surface and infrastructure allows researchers to differentiate street, yard, and landscaped park trees from patches of contiguous forest (Pregitzer et al. 2021; Alonzo et al. 2021; Sonti et al. 2024). Advances in remote sensing and geospatial analysis also allow large scale mapping of individual forest patches across entire landcapes (Gounaridis et al. 2020; Reinmann et al. 2020; UMD et al., 2022; Chesapeake Bay Program, 2023). Identifying and delineating forest patches, those areas where natural regeneration and establishment of woody species occurs, allows managers to focus on forest ecosystem services (Pregitzer et al. 2021; Johnson et al. 2021; Baker et al. in press). In urban and suburban settings in particular these forest patches are critical for their high native plant diversity, recreational opportunities, wildlife habitat, and contributions to carbon sequestration (Nitoslawski et al. 2016; Johnson et al. 2021; Jevon et al. 2024)

Documenting the distribution, land ownership, and use of forest patches therefore can reveal important nuances of how forest ecosystem services are maintained for diverse publics, and across a range of potential management agencies (Morzillo et al. 2022). In this study, we explore the distribution of forest patches in three regions that follow an urban-rural gradient: within Baltimore City, in the suburban portion of Baltimore County, and the rural portion of Baltimore County (Fig. 1) (Baltimore City is a separate, independent jurisdiction from Baltimore County, surrounded on all sides by Baltimore County). We use high resolution land cover and morphological spatial pattern analysis (MSPA) (Soille and Vogt, 2009; Vogt and Riitters, 2017) to distinguish forest patches from other forms of tree canopy (Fig. 1). Given our interest in forest management and conservation across ownership and parcels, we focus on ownership and land use for forest cover but also within individual patches. Baltimore City and Baltimore County make an apt study area because the city, county, and state of Maryland have long histories of land use planning and forest conservation (Irwin et al. 2019; UMD et al., 2022). The URDL was the second urban growth boundary created in the United States, and Baltimore County is widely recognized for their

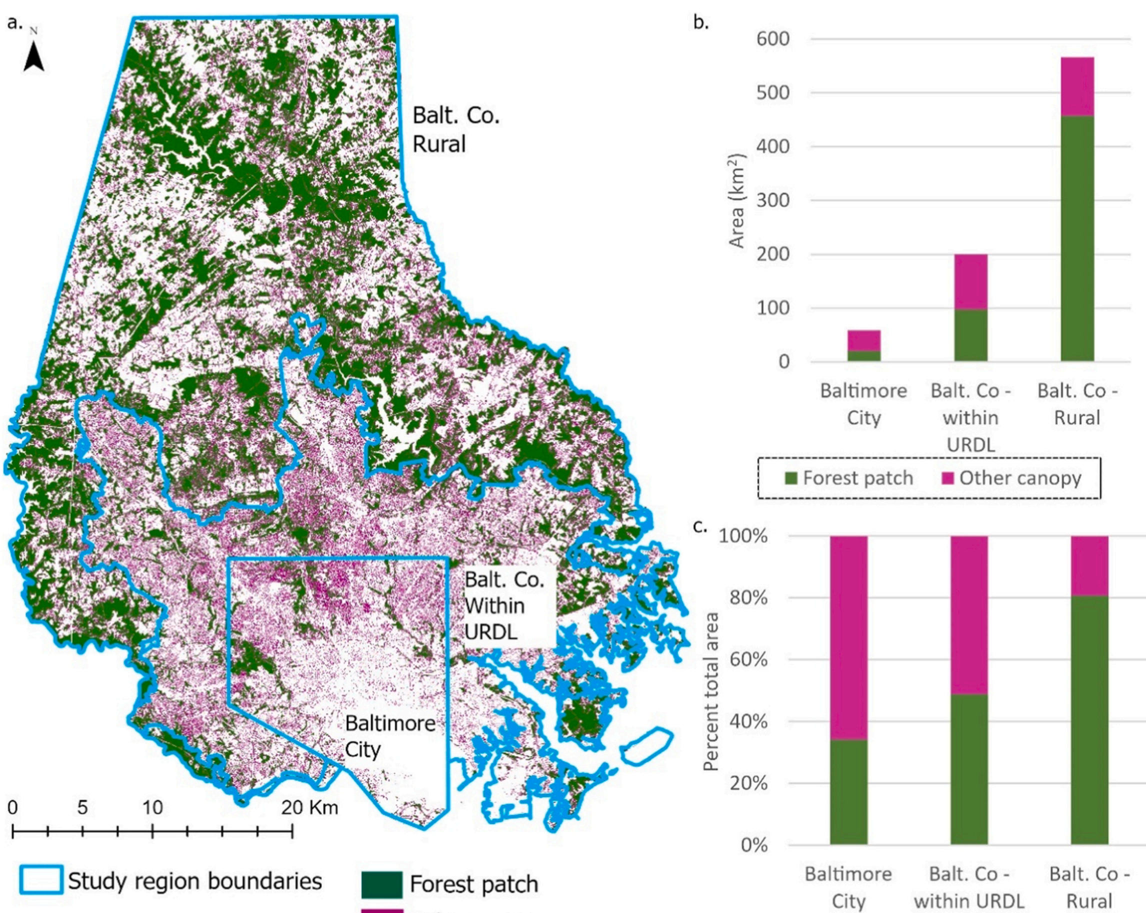

Fig. 1. a. Map of forest patches and other tree canopy cover across study area, which includes Baltimore City and two areas within Baltimore County, the suburban portion below or within the URDL and the rural portion of the county that is north or outside of the URDL. Baltimore City and Baltimore County are separate, independent jurisdictions. Other tree canopy includes isolated smaller areas of tree canopy cover and those trees that overhang impervious surfaces. Inset figures show the b) total area and c) percent of total area for forest patches and other canopy for each region in the study: Baltimore City; the portion of Baltimore County within the URDL; and the rural portion of Baltimore County outside the URDL.

success in protecting rural and agricultural lands (Hundt Jr. and Daniels, 2018).

Based on previous studies, we anticipated we would find differences between regions for forest patch size, total extent, and ownership (Zhou et al. 2011; Zipperer et al. 2012; Gounaridis et al. 2020). We expected Baltimore City would have smaller forest patches on average, less forest cover, and more public ownership in comparison to rural Baltimore County, which we anticipated would have larger patches, more forest cover, and more private ownership (Zipperer et al. 2012). Given our expectation that forest patches would be larger in rural Baltimore County, we also expected patches would encompass more parcels than in the city, and represent a greater diversity of ownership and use per patch. We anticipated total forest cover would be intermediate within the suburban portion of Baltimore County, between city and rural cover, but we did not have other *a priori* expectations for how the number, size, and ownership and land use of patches might vary in comparison to urban or rural areas. Contrasting the distribution and character of forest patches in suburban with urban and rural contexts is a novel contribution of this paper; such 'in-between' settings are less well understood than urban or rural extremes (Colgan et al. 2014; Johnson et al. 2023). Finally, focusing on the forest patch as the unit of analysis, in combination with parcel data, allowed for additional insight into the maintenance and future management of forests: for example, identifying location of the largest forests, recognizing the need for varied outreach based on landowner types, and understanding the value of cross-parcel management.

2. Methods

2.1. Study area

Baltimore County extends over 1575 km^2, surrounding the land-based boundary of the city of Baltimore (209.5 km^2) and extending north to the state border with Pennsylvania (Fig. 1). Baltimore City and Baltimore County have been separate units of government since 1851. To contain urban expansion and conserve agricultural and forested lands, Baltimore County adopted an urban growth boundary in 1967, termed the Urban-Rural Demarcation Line, or URDL which divides the county into a suburban area where growth is concentrated. There are three regions in this analysis: Baltimore City, suburban Baltimore County within the URDL, and a rural portion of Baltimore County where growth is restricted, also referred to as outside the URDL (Fig. 1).

Forests in the region are primarily composed of oak-hickory overstories, with beech-tulip-poplar canopies present on more mesic sites as well (Brush et al. 1980; Hanberry and Nowacki, 2016). As with the majority of the US Eastern seaboard, forests in the region were actively managed by and were critical resources for indigenous communities, but were widely harvested and converted to agriculture after the arrival of European colonists, a trend that continued until the Civil War (Brush and Bain, 2019; Maryland Department of Natural Resources, 2020). By 1890, much of Maryland had been deforested, and in response, professional forestry and park systems in the state and study area expanded (Bain and Buckley, 2019). Neighborhood groups were actively enlarging and managing green space in Baltimore City from the early 1900s (Irwin et al. 2019).

Population grew rapidly in Baltimore City and surrounding areas in the first half of the 20th century. After World War II, the city declined in population, as a result of post-industrial economic change, white flight, and broader suburbanization, similar to other cities in the Midwest and eastern US (Bain and Buckley, 2019). Population and economic decline contributed to vacant lots (an estimated 18,000 in Baltimore City), some of which are forested (Avins, 2013). As the city population declined, residential development and population expanded dramatically in the surrounding Baltimore County, which further removed and altered forest cover (Zhou et al. 2011).

As suburban development in Baltimore County continued after World War II, the County instituted the URDL in the late 1960s (Irwin et al. 2019). Zoning and septic system controls, along with active private land conservation efforts have all focused on limiting development in the rural portion of the county (Baltimore County, 2023). Today, almost 90 percent of the county's population lives within the URDL, which is just one-third of the county's land area. A total of 276.5 km^2 (27 % of the land) outside the URDL is preserved in private easements through a variety of programs, aimed at protecting agricultural land, rural lifestyles, and forest (Baltimore County, 2022; Neighbor Space, 2024). Forest in Baltimore County now has many mature stands, aged from 100 to 120 years (Mar-Len Environmental and Baltimore County, 2007; Lister and Widmann, 2016). Forested areas here play a key role in protecting and maintaining drinking water for the region, including Baltimore City, Baltimore County, and four other counties. Baltimore City operates the water system and owns the reservoirs, but most of the watershed area falls within Baltimore County.

2.2. Creating forest patch data

We created a map of forest patches starting with a high resolution (1 m) canopy layer from a classified land cover map based on 2013/2014 imagery (Chesapeake Conservancy, 2018). We removed any canopy that overlapped with buildings and roads (derived from planimetric data from 2008 and 2015 from Baltimore City and County), leaving a layer of tree canopy that does not overlap with impervious surface (i.e., "soft canopy"; Alonzo et al. 2021). More recent versions of the land cover maps will distinguish such canopy classes *a priori*. Morphometric Spatial Pattern Analysis (MSPA; Soille and Vogt, 2009; Vogt and Riitters, 2017) was applied to the soft canopy layer to identify contiguous groups of cells farther than 15 m from canopy edges, with each group of these connected cells assigned a unique identifier (Alonzo et al. 2021). MSPA distinguishes such interior cells as "cores" as well as their surrounding edges and edges around interior gaps ("perforations") from other forms of canopy too narrow to contain interior space. The edge width of 15 m was based on forest patch vegetation field surveys within Baltimore City, where significant structural and compositional shifts in both overstory and ground layer species 15–18 m from canopy edges was observed (Baker et al. in press). The minimum possible forest patch was thus circular, with edges of 15 m on either side of a core pixel of 1 m x 1 m, for an area 793 m^2. Forest patches therefore excluded any isolated smaller areas of tree canopy cover and those trees that overhang impervious surfaces (Fig. 1). We limited all forest patches by the extent of our study area. For each study region, we present area for both forest patches and for other tree canopy, and then focus our analyses on patches.

We overlaid forest patches with 2015 parcel data from State Department of Planning (Maryland Department of Planning, 2015) to assign forest patches to individual parcels, yielding 133,570 intersections between forest patches and parcels. We further examined parcel data to determine land use and ownership. We purposefully included ownership and land use separately as land uses can cross ownership classes, or vice versa. For example, local government can own land with a variety of uses (e.g., parks, schools, transportation, and offices), and park and recreation areas can be owned by public (federal, state, local) and private owners. In some cases where state-level data were missing or inconsistent, we turned to additional publicly available data. For Baltimore County, we drew upon a publicly available land use layer (Baltimore County, 2018), for those parcels where we could not determine ownership or use from state-level data. For Baltimore City, we used additional resources including Google Maps imagery, public records, consulting with City staff to improve data on ownership and use (Sonti et al., in press). After compiling parcel data on ownership and use, authors worked collaboratively to condense ownership and land use. For land ownership, we had three types of public land ownership (federal, state, local) and three types of privately-owned land (commercial/industrial, institutional, and other private ownership). Local ownership could be Baltimore City or County, but there are no incorporated municipalities such as towns or cities within Baltimore County. We combined these ownerships with six land use types: agriculture, schools, transportation (bus station, railway), park/recreation (parks and open space, golf courses, and recreational facilities), residential, and other institutional use (hospitals, nursing homes, church, library, cemetery) (Supplemental Figure 1). This initial analysis revealed the predominance of three main land use categories—agricultural, parks and recreation, and residential—each of which had a consistent association with either private or public ownership. We therefore focused on these most common *combinations* of ownership and land uses: 1) privately-owned residential (Priv-Res), 2) privately-owned agricultural (Priv-Ag); 3) publicly-owned park and recreation (Pub-Park), 4) privately-owned other use, including unknown use (Priv-Oth), and 5) publicly-owned other use, including unknown (Pub-Oth), and 6) unknown ownership and use (Unknown).

2.3. Analyses and summaries

Working in R (4.1.2) (R Core Team, 2023) we summarized data on forest patches across the entire study area and for each region (in the city, within the URDL, in the rural portion of Baltimore County). We characterized forest patches by number and size for each region, and then examined total area in forest patches (hereafter, forest area) by region, for each ownership and land use, and then ownership and land use combined. Although the overlap between forest patches and parcels could be small (see Section 3.3), we retained any overlap when calculating totals for ownership and land use across the regions.

Our analyses required additional investigation of the data so that small intersections of a forest patch with a parcel (i.e., slivers) did not lead to inflated counts of parcels or ownership and use. We examined our data of forest patch and parcel intersections ($n = 133{,}570$), sequentially removing small areas of forest patch by parcel (less than or equal to 25, 50, 100, 250, and 500 m^2), and considering the resultant reduction in number of observations, forest patches, and total forest patch area in our data. We found removing parcel and forest patch intersections of 100 m^2 or less was an acceptable compromise: it did not remove any forest patches from our data set, and only removed 1.24 km^2 of forest area, but did eliminate 29.2 % of our intersections of forest patches and parcels, reducing from 133,570 to 94,585 of these intersections. Once we removed small slivers of < 100 m^2, we then recalculated metrics of interest for each forest patch: number of parcels that fell within a forest patch, size of forest on each parcel, and the total size of the forest patch.

Forest patches that spread across multiple parcels may experience a range of land uses and ownership types. Using our six combinations of ownership and use, Priv-Ag, Priv-Res, Priv-Oth, Pub-Park, Pub-Oth, and Unknown, we counted the number of owner and land use types found per forest patch (Fig. 2). For example, a forest patch comprised of five parcels, all Priv-Res ownership and land use would be considered one type of ownership and land use. For each forest patch our analyses yielded the number of parcels and a count of ownership and use types. We note that we could not consider individual property owners: for example, a city park or university might be represented in the parcel data as multiple parcels, divided by infrastructure or other features such as roads or buildings. Given the complexity of the ownership records, particularly for private parcels, it was not possible to further winnow to unique owners. For each of our study regions, we summarized area for each combination of ownership and use, and determined the largest combinations of ownership and use, number of patches, and parcels per patch.

Given our interest in forest management and conservation across ownership and parcels, we also display largest forest patches ($n = 40$) in our study region size. Size for these largest 40 patches ranged from 1.87 km^2 to 5.57 km^2. We present the location of the largest patches and summarize patch area and ownership. We chose the largest 40 patches because they are readily visualized on a map of the study area, contain just over 20 % of all forest in the study area, and reveal a range of land ownership and uses.

3. Results

3.1. Area and number of forest patches

Forest patches made up the majority of total tree canopy in the rural area of Baltimore County (80.7 %), but less than half of tree canopy in the suburban portion of Baltimore County (48.8 %) and 34.2 % of tree canopy within Baltimore City (Fig. 1c). Total area of other tree canopy including street trees was similar in the suburban portion of Baltimore County and rural portion of the county, at over 100 km^2, but was closer to 40 km^2 in the smaller Baltimore City (Fig. 1b). Hereafter, analyses focus solely on forest patches.

Across our entire study area we found 20,146 unique forest patches, a total 581.9 km^2 in area, which accounted for nearly one-third (32.6 %) of the study area (Table 1). Moving from urban to rural, the number of forest patches, mean, median and maximum forest patch size, and total forest area, as well as proportion of land area covered by forest patches, all increased (Table 1, Fig. 1a). Although differences in patch size across regions were statistically significant (Kruskal-Wallis chi-squared = 95.9, df = 2, p-value $< 2.2\text{e-}16$), with pairwise comparisons revealing differences among all regions, median forest patch size was small across all regions, ranging from just over 2100 m^2 in Baltimore City to more than 2600 m^2 in the rural portion of Baltimore County (Table 1).

The total area in forest per region reflects the number of forest patches, forest patch size, and study region size. For the rural portion of Baltimore County where there were more forest patches and forest patches were larger in size, forest area was largest, both in absolute area and percent of total land area (Table 1). In total, the rural portion of Baltimore County has 44.7 % forest land cover, makes up nearly 59 % of the study area, and has an estimated 85,000 residents (Table 1). For the entire study area, the largest 40 forest patches (≥ 1.87 km^2) were found only in the rural portion of Baltimore County. The area inside the URDL has 17.9 % of land cover in forest patches, makes up nearly 30 % of our study area in size, and an estimated 764,400 people. Baltimore City, with 9.7 % of total land cover in forest patches, is home to 585,700 people, and makes up 11.8 % of our study area in size. When considering the number of patches relative to land area, the entire study area had 11.2 patches per km^2, compared to 9.5 patches/km^2 in the city, 14.6 patches/km^2 in suburban Baltimore County, and 10.0 patches/km^2 in the rural part of the county Fig. 2.

3.2. Ownership and land use of forest patches

Drawing on parcel data for nearly 95,000 parcels, we were able to determine ownership for 89 % or more of forest patch area by region (Table 2). For the entire study area, we were able to assign land use for nearly all (94.1 %) privately-owned forest, but only for two-thirds of the publicly owned forest (Supplemental Figure 1). Across all regions, where we could determine land use of publicly owned forest, these patches were primarily in park and recreational use and with state and local ownership (Supplemental Figure 1). In total, 4.5 % of forest in the entire study area had both unknown ownership and unknown use (25.9 km^2 area) (Table 2).

As anticipated, public ownership was more common for forest in the city. Within Baltimore City, 54.6 % of forest was publicly owned (Table 2), nearly all by city government (Supplemental Figure). For privately-owned forest in Baltimore City, use was divided between residential (20.7 % of total forest area in the city), and other uses (20.2 % of total forest area (Table 2). As expected, private ownership was more common in the county, and made up most of the forest area within the URDL and rural portion of the county (Table 2). Within the URDL, privately-owned residential areas (Priv-Res) had the largest share of

Table 1
Forest patch summary statistics by region. Superscripts for median area denote pairwise comparisons with non-parametric Wilcoxon rank sum test; all regions were statistically significantly different from each other (p = 0.02 for city and URDL comparison, p < 0.001 for other comparisons).

		Forest patches						**Land area**		
Region	Pop.	Count	Median area (m^2)	Mean area (m^2)	Min. area (m^2)	Max. area (m^2)	Sum area (km^2)	Total area (km^2)	% land in forest	Patches (n)/ km^2
City	585,708[1]	1944	2113[a]	10,456	792	1040,987	20.3	210	9.7 %	9.5
In URDL	764,384[2]	7708	2279[b]	12,268	792	2134,608	94.6	529	17.9 %	14.6
Rural	84,932[2]	10,494	2615[c]	44,469	791	5568,856	467.0	1046	44.7 %	10.0
Total	*14,350,245*	*20,146*	*2418*	*28,867*	*791*	*5568,856*	*581.9*	*1785*	*100 %*	*11.3*

1. 2020 decennial census (U. S. Census Bureau 2022a)
2. 2020 decennial census for Baltimore County is 849,316 (U. S. Census Bureau 2022b); calculated population within the URDL based on estimated 90 % of population lives within the URDL (Baltimore County, 2022).

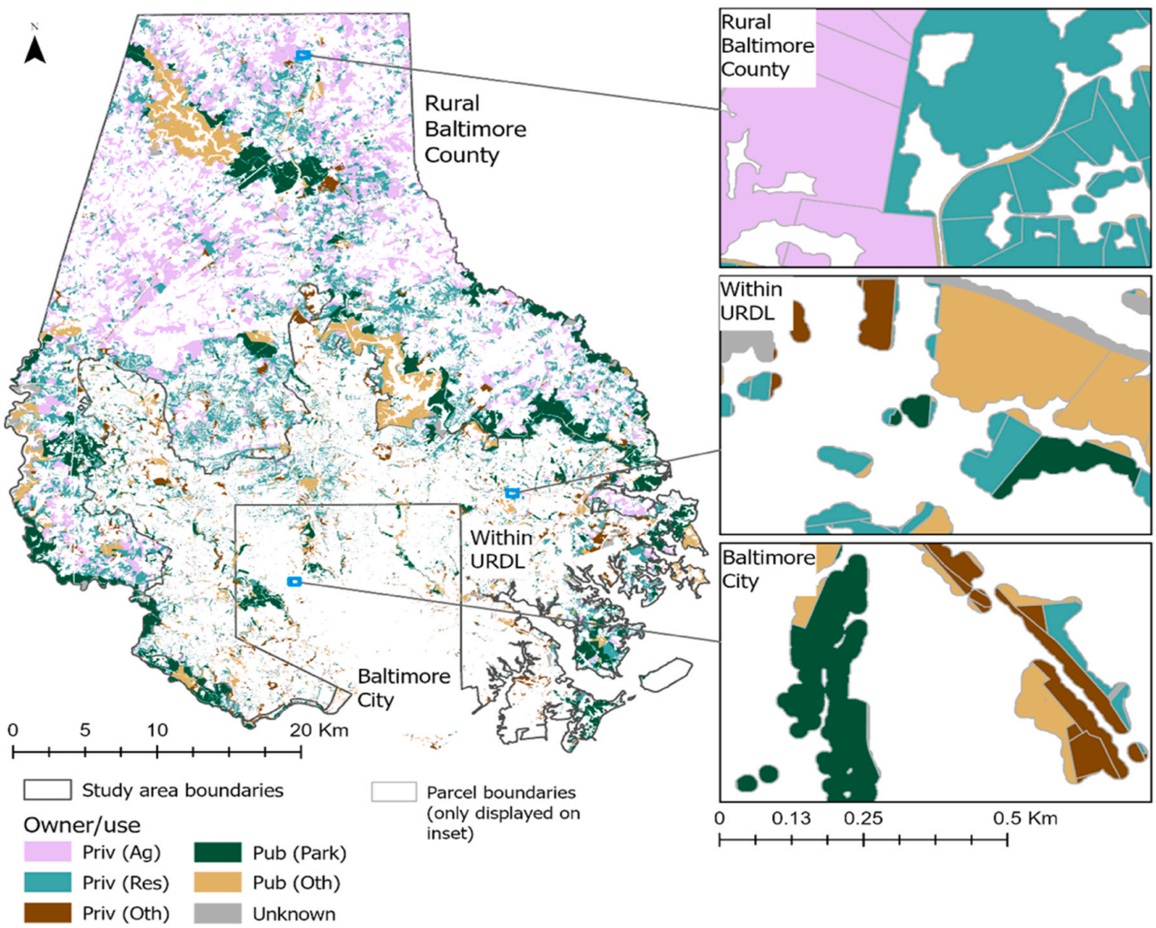

Fig. 2. Distribution of forest patch land ownership and use for each study region with inset maps showing example patches and parcel boundaries for Baltimore City, area within the URDL of Baltimore County, and rural Baltimore County.

Table 2
Ownership and use of forest patch area by region, in total area (km^2) and percent of all forest patch area in the region.

	City		**County – In URDL**		**County – Rural**	
Owner (Use)	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
Public (Park)	7.6	37.4	12.6	13.3	85.6	18.3
Public (Other)	3.5	17.2	14.8	15.7	49.1	10.5
Private (Ag.)	0	0	1.4	1.5	159.3	34.1
Private (Res.)	4.2	20.7	36.9	39.0	143.3	30.7
Priv (Other)	4.1	20.2	18.8	19.9	14.2	3
Unknown	0.9	4.4	10.0	10.6	15.1	3.2
Total	**20.3**	**100**	**94.5**	**100**	**466.5**	**100**

forest area (39 %), with an additional 16 % of all forest in other use. In the rural portion of Baltimore County, privately owned agricultural land (Priv-Ag) was the largest category of ownership and use (34 % of total forest area), closely followed by private residential (Priv-Res) (30.7 %) (Table 2). Within the county, public ownership made up a similar proportion within the URDL and in the rural portion of the county, approximately 29 % of forest area in each (Table 2).

Examining where the different combinations of ownership and use are found in each area (Fig. 3) shows publicly owned park and recreation use (Pub-Park) concentrated in river valleys and around water supply reservoirs in rural Baltimore County, including on the eastern boundary of the URDL, and as well as in Baltimore City (Gwynns Falls/Leakin Park and Herring Run areas) (Fig. 3). Forest in privately-owned residential areas (Priv-Res) in rural Baltimore County was concentrated in the

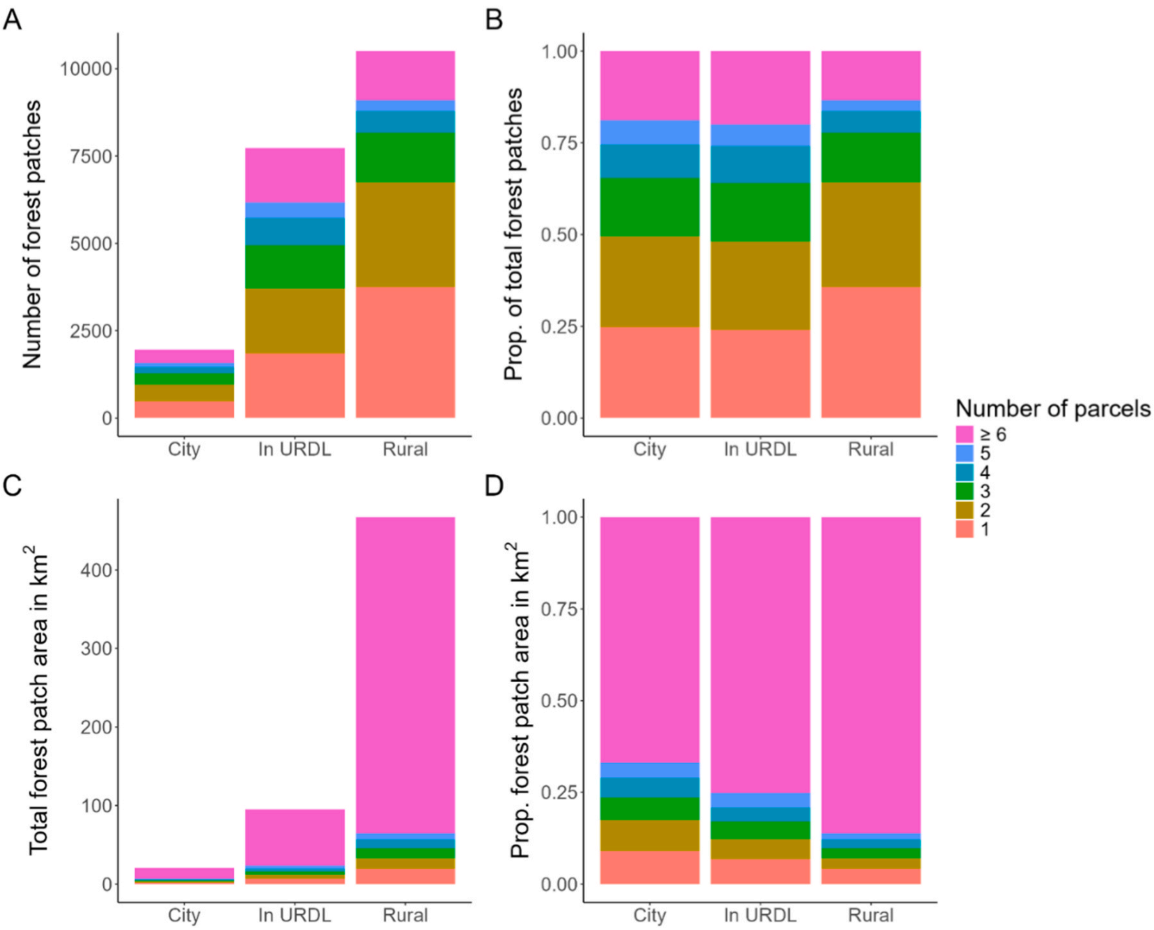

Fig. 3. Number of parcels per forest patch, ranging from one parcel to more than six, by region: (a) count of forest patches by number of parcels per patch; (b) proportion of total forest patch count by number of parcels per patch; (c) area of forest patches by number of parcels per patch, and (d) proportion of total forest patch area by number of parcels per forest patch.

southern portions of the rural study area, and along the Interstate-83 highway that extends from Baltimore City north to Pennsylvania. Forest in Priv-Ag ownership and use was found throughout rural Baltimore County, especially in the northern part of the county (Fig. 3).

3.3. Characterizing forest patches

Remaining analyses focused on individual forest patches, drawing on parcel data to characterize the number of parcels and the diversity of ownership and land use types per forest patch, and comparing the three regions in our study area. For these analyses we excluded any parcel and forest patch intersections of 100 m^2 or less, so that small intersections of a forest patch with a parcel (i.e., slivers) did not lead to inflated counts of parcels per forest patch, or types of ownership and use.

3.3.1. Forests patches by parcel

For each region in our study area, forest patches most commonly fell on one or two parcels. In total, patches with two or fewer parcels included 50 % of all forest patches in the city, 48 % inside the URDL, and 64 % in the rural portion of the county (Fig. 4a, b). From nearly a quarter to just over a third of patches in each region fell onto only one parcel, so that conservation and management of that forest patch would fall to one owner (Fig. 4a, b). However, forest patches with one or two parcels were smaller in size, and made only a minor contribution to total forest area (Fig. 4c, d). Forest patches that spanned six or more parcels were less common in our study, but they made up the majority of forest area, and a larger relative contribution to area when moving from urban to rural regions: patches with six or more owners made up 67 % of forest area in Baltimore City, 75 % in the URDL, and 86 % in rural Baltimore County (Fig. 4b, d).

3.3.2. Forest patches by ownership and land use

For each region, the largest forest area came from patches that included every type of ownership and use, both privately and publicly owned land (Table 3). For example, patches that included parcels with all types of ownership and land use—Priv-Res, Priv-Other, Priv-Ag (only in rural Baltimore County), Pub-Park, Pub-Other, and unknown ownership and use—made up 3.4 km^2 forest area in Baltimore City, 10.1 km^2 within the URDL, and 56.2 km^2 in rural Baltimore County (Table 3). These patches that included every type of ownership and land use were comprised of many parcels: a median of more than 25 parcels in Baltimore City and within the URDL, and a median of nearly 100 parcels in rural Baltimore County (Table 3).

In each region, privately owned forest area was among the top five combinations of ownership and use, as measured by area (Table 3). For example, in rural Baltimore County, 1100 patches that spanned agriculture and residential use made up 32.5 km^2; within the URDL forest patches on private residential land included more than 2180 patches over 6.4 km^2, and in Baltimore City more than 400 forest patches on private residential land totaled 0.9 km^2. In each region, these forest patches with private land ownership included a median of three parcels: collaborating across parcels here would mean working over a smaller number of parcel owners, similar ownership types and land uses, and on parcels that could be more readily sold or developed, in comparison to publicly owned park and recreation land. Only in Baltimore City was public land alone among the top five largest forest areas: of the 20.3 km^2

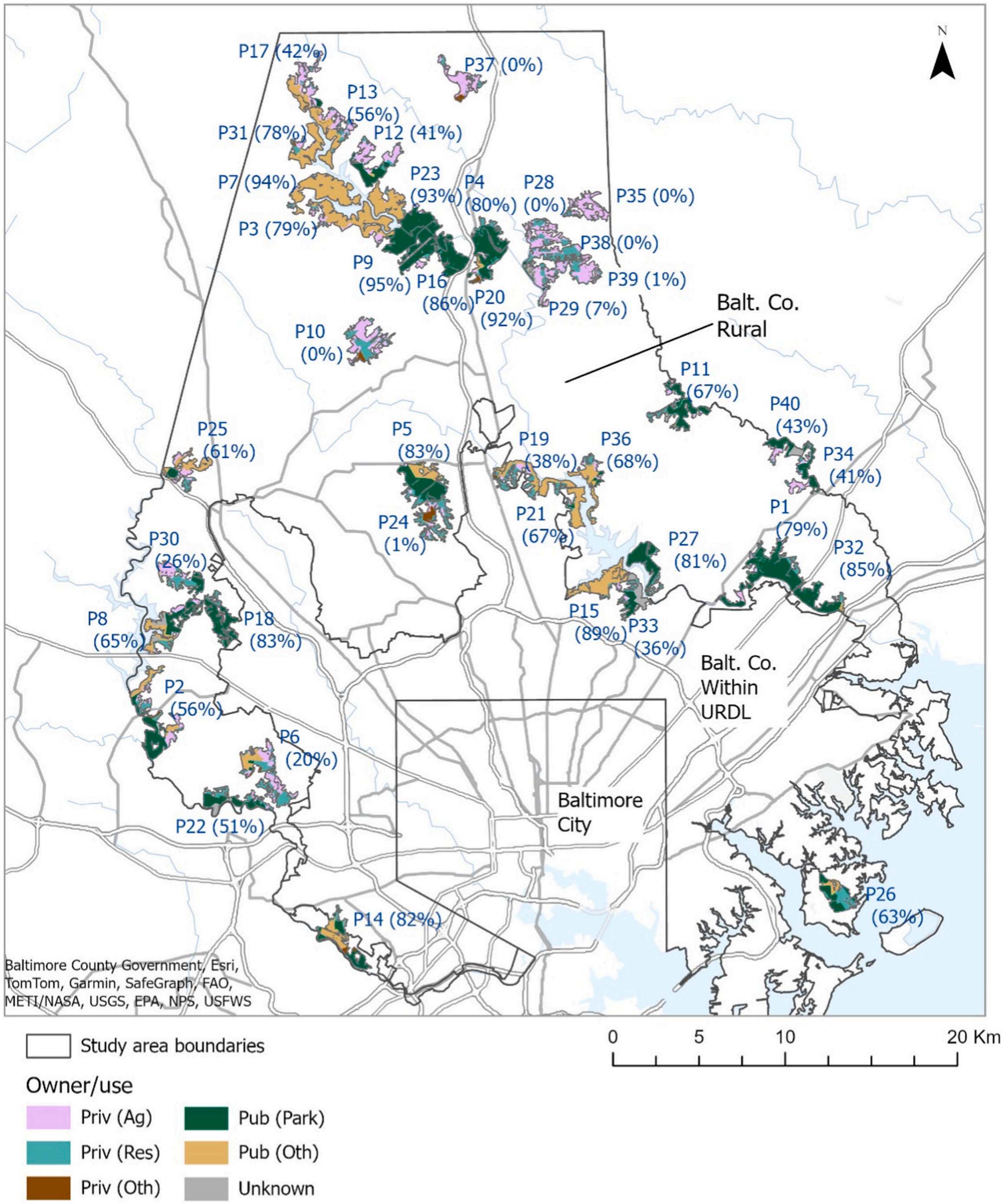

Fig. 4. Largest forest patches (n = 40) by ownership and use. Patches are labeled sequentially in size from P1 (the largest patch) to P40 (the smallest patch), with proportion of public land in parentheses for each patch (e,g, P2 is the 2nd largest patch in our study, with 56 % of land that is publicly owned).

of total forest area in the city, 1 km^2 was found on patches that fell only on Pub-Park parcels (Table 3).

Given our interest in forest management across ownership and parcels, we also examined ownership and use for the 40 individual largest forest patches in our entire study area (Fig. 4). All these largest patches were in the rural part of Baltimore County, ranged from 1.87 km^2 to 5.57 km^2 in size (median 2.62 km^2), and contained a variety of ownerships and uses. Of 40 patches, 25 were primarily in public ownership, whereas 15 were predominately private ownership. Private land use was mostly agriculture with a small residential component: 38 of 40 patches contained both Priv-Ag and Priv-Res and two contained only Priv-Res (Fig. 4). Public land use was a mix of park and recreation and other uses. When shown on a map, many of the largest forest patches were located in the northern section of rural Baltimore County in proximity to each other, with 1 km or less separating patches.

4. Discussion

Expanding development and shifting land uses pose significant threats to forests, especially in the eastern US, where there is a long history of urban and suburban development (Sleeter et al. 2013; Van Berkel et al. 2018). At the same time, people in this region rely on forest ecosystems and their benefits. In this study, we utilized a high-resolution dataset of tree canopy cover to map over 20,000 forest patches across

Table 3
Table shows the combinations of ownership and land use that comprised the largest total forest patch area, by region. With the exception of publicly owned park land in Baltimore City, forest patches spanned multiple parcels, so we display median number of parcels per patch, and the summary statistics for mean percent area found in any one parcel.

Region	Combinations of owner/use	Sum patch area (km^2)	No. of forest Patches	Area largest patch (km^2)	Median number parcels, per patch	Per forest patch, mean % area in a parcel		
						Min	Mean	Max
Balt. City	Priv (Res, Oth) + Pub (Park, Oth) + Unk	3.4	12	0.9	25	1.1	4.0	6.7
	Priv (Res) + Pub (Park, Oth) + Unk	2.5	12	1.0	16	1.1	8.4	16.7
	Priv (Res, Oth) + Pub (Oth) + Unk	1.5	27	0.3	17	1.0	7.5	25.0
	Pub (Park)[a]	1.0	149	0.2	1	100	100	100
	Priv (Res)	0.9	413	0.0	3	4.3	31.2	50.0
In URDL	Priv (Res, Oth) + Pub (Park, Oth) + Unk	10.1	64	1.3	27.5	0.8	4.7	16.7
	Priv (Res) + Pub (Park, Oth) + Unk	8.8	115	0.4	18	0.8	7.4	25.0
	Priv (Res, Oth) + Pub (Oth) + Unk	8.7	90	0.9	15.5	0.5	8.5	25.0
	Priv (Res)	6.4	2187	0.1	3	2.4	34.0	50.0
	Priv (Res) + Unk	6.3	754	0.3	3	1.3	30.2	50.0
Rural	Priv (Ag, Res, Oth) + Pub (Park, Oth)+ Unk	56.2	27	5.6	97	0.4	1.6	11.1
	Priv (Ag, Res) + Pub (Oth)	52.1	266	4.2	9	0.7	14.1	33.3
	Priv (Ag, Res) + Pub (Park, Oth) + Unk	35.9	23	4.4	77	0.5	1.9	8.3
	Priv (Ag, Res)	32.5	1100	1.4	3	1.9	33.6	50.0
	Priv (Ag, Res, Oth) + Pub (Oth)	30.4	59	2.3	29	0.7	5.8	25.0

[a] Forest patches on public park land in Baltimore City were on only one parcel.

Baltimore City and Baltimore County, spanning urban, suburban, and rural areas. Comparing these three regions emphasizes the importance of suburban areas and privately owned areas in maintaining forests. The high resolution data also allowed us to focus on individual patches, underscoring the prevalence of small patches with one or two owners in our study, and the importance of managing forest patches across parcel boundaries to maintain larger forest areas.

4.1. Forest distribution across regions

When comparing the three regions, as predicted, suburban forests were in many ways intermediate between the densely built environment of Baltimore City and rural areas of Baltimore County. Number of forest patches, their median size, and the frequency of patches spanning multiple parcels were highest in rural areas, lowest in urban settings, and in between in suburban regions, consistent with findings elsewhere (McDonnell and Hahs, 2008). Considering development patterns, however, the amount of forest cover within suburban areas is notable: although this part of the county makes up one-third of Baltimore County's total area, it holds approximately 90 % of the county's population, at nearly ¾ million people. Despite the intensity of development, a total of 17.9 % of land area is in forest, with more patches per area than in other regions, with a similar area in street trees and other tree canopy. In our study, ownership and use within the URDL was also unique: suburban forests are predominantly under private residential ownership and use (39 % of all forest area), contrasting with the public ownership seen in urban areas and the agricultural ownership common in rural Baltimore County.

These findings have implications for future conversion, forest management, and public access. Given the long-standing nature of the urban growth boundary, and emphasis on agricultural preservation in rural Baltimore County, forest within rural Baltimore County may be less prone to conversion than forests within the URDL, which differs from other settings where development is the greatest threat to rural forest cover (Bonney and He, 2019). At present, many of these agricultural lands are protected under easement, but only some of these programs focus on forest restoration and others focus on agricultural preservation (Baltimore County, 2023). Investigating the role of private land easements in forest cover could further provide insight into opportunities for and threats to forest cover. For agricultural areas, forest cover might be further incentivized over time, through markets for carbon (Lamb et al. 2021), as part of broader efforts to restore the Chesapeake Bay. Privately owned forest patches within Baltimore City and within the URDL are likely more vulnerable to conversion, given that development will continue within the URDL and that in comparison to other cities (New York, Philadelphia), Baltimore City retains relatively more forest on private ownership (Sonti et al., in press).

Across regions and ownerships, level of forest management also likely varies. Researchers and practitioners are working to adapt forest management plans and practices to ensure the maintenance and health of small forested patches in more developed settings (Piana et al. 2021; Romanelli et al. 2024) but existing forest inventories and management plans typically focus on publicly-owned land in urban areas (e.g., Forgione et al. 2016; Mojzak et al. 2020 but see Baltimore Green Space (2022)). Residents and homeowners in developed areas are often deeply engaged in management of individual trees in landscaped areas (Pearce et al. 2015; Ossola et al. 2019; Pike et al. 2023), but management of forest patches on private residential land is less common (Colgan et al. 2014; Hutt-Taylor and Ziter, 2022; Romanelli et al. 2024). Studies that examine forest structure and biodiversity in relation to ownerships and land use histories are also needed to better understand forest in these mixed-ownership landscapes (Mölder, 2021; Schmit et al. 2025).

Finally, forest patch extent and ownership have implications for access. In these more densely developed areas (within the URDL and Baltimore City), although forest patch total area is smaller, it is located in proximity to a larger number of people. Additional research is necessary to understanding access and use of forests across public and private land, and to elucidate how forest patches can provide ecosystem services (Boone et al. 2009; Grove et al. 2018; Locke et al. 2021; Darling et al., 2024/5). Even within Baltimore City, where much of the forest is on publicly owned land, not all of it is park land (Sonti et al., in press), which may have implications for physical access or community perceptions of forest suitability for recreation.

4.2. Forest patches by size and parcel

Across all three regions, most forest patches spanned one to two parcels and median forest patch size was relatively small (2100 to

2600 m^2). However, in all three regions we considered, patches that spanned multiple ownerships and land uses contributed far more to total forest area, highlighting the complexity of managing these diverse landscapes. Coordinating forest management at a patch level would require working across many parcels, and public and private use. Existing literature on cross-boundary or collaborative forest management typically focuses on rural settings where forested amenities or livelihoods may be central to residents' daily lives (Niemiec et al. 2020; Charnley et al. 2020; Clarke et al. 2021); the dynamics of collaborative management in suburban and urban areas are less clear, yet potentially more complex with more and varied stakeholders.

When multiple owners are connected to a forest patch, misaligned management objectives or unclear responsibilities could adversely affect forests. Particularly when public and private ownership mix, there may also be a lack of clarity or agreement on shared responsibility for some management actions, such as removing hazardous trees, preventing fires, or controlling invasive species. Longer-term protection through conservation easements and land acquisitions are complicated as well, as they typically do not focus on multiple owners. Conversely, a forest patch on one property concentrates the responsibility for forest management, which could lead to benefits and drawbacks. A single ownership can simplify transactions to protected status, but can also lead forest to be more readily sold or converted, whereas absentee ownership may mean little or no monitoring, increasing risk of invasive species takeovers in forest patch areas, dumping, or similar forms of degradation. Despite some case study evidence on these management challenges, there remains a lack of empirical data on the connection between multiple ownership and forest patch health across the urban-to-rural gradient (Ossola et al. 2019; Johnson et al. 2023). The experiences of working across parcels and ownership types might vary based on location, parcel, and forest conditions, but the value and need for such cross-boundary collaboration and learning is likely to be widespread, both in Baltimore and other urban and urbanizing areas throughout the United States and beyond.

As research and management efforts aim to bridge urban and rural settings in forest restoration, the variation in forest patch sizes—from small fragments under 1000 m^2 to extensive patches up to 5.6 km^2—presents both challenges and opportunities for integrating restoration efforts across diverse landscapes and communities (Romanelli et al. 2024). Many of the attempts to address green space access focus on augmenting tree canopy through planting, typically street trees or other landscaped settings (Locke et al. 2013; Burghardt et al. 2023). Investment in forest patches, might take a different form, with greater emphasis on conservation, restoration, and active use, spanning public and private actors (Avins, 2015; Bowers et al. 2020; Morzillo et al. 2022). For example, in Baltimore City, the non-profit organization Baltimore Green Space focuses on ~15 community-maintained forest patches managed by neighborhood forest stewards. Stewards often live near the forest patch that they care for, which may be on public or private land, and have long-running personal attachments to these areas (Morzillo et al. 2022).

4.3. Limitations

Our findings in part reflect choices made during analysis, including the exclusion of forest cover over impervious surfaces such as roads and the 15 m edge width used to delineate patches. These decisions reflect our emphasis on forest ecosystem function as well as transitions observed in forest vegetation structure and composition (Alonzo et al. 2021; Sonti et al. 2024, Darling et el. in press, Baker et al. in press). We acknowledge that edge effects for different taxa and ecosystem processes may vary (Matthews et al. 2016; Ries et al. 2017) However, retaining smaller forests provides a full picture of woodland extent, and smaller forest patches can make valuable contributions to multiple ecosystem services, particularly when they contain larger or older trees (Mitchell and Devisscher, 2022). Including additional information about forest age, condition, vertical structure, and landforms—as well as proximity between forest patches—will be vital in better understanding the conditions and ecosystem functions provided by smaller patches and over landscapes (Baker et al. in press).

We note as well that our analyses relied on parcel data to discern ownership and land use, we used three broad classifications of development (city, within the URDL, outside the URDL), and focused on forest cover at one moment in time. Ownership and land use can be nuanced beyond what we can gain from parcel data, and development and land use histories are also complex, with dynamic and sometimes unexpected results on forest cover (McDonnell and Hahs, 2008; Zhou et al. 2011; Roman et al. 2018). For example, as residential development expands into agricultural areas, and as trees mature, forest canopy can increase with development (Gounaridis et al. 2020). Integrating additional information on past and present land use with forest condition and ecosystem services at multiple scales can provide additional insight into the maintenance of forests across different settings. (Nitoslawski et al. 2016).

5. Conclusions

Across Baltimore City and Baltimore County, we identified over 20,000 forest patches in rural, suburban, and urban settings. Size and number of forest patches, as well as the proportion of forest spanning multiple parcels and on private lands, all increased when moving out from urban to rural areas. Baltimore County's urban growth boundary means that rural portions of the county have substantial forest, often on or near lands designated for agricultural use. Baltimore City's forest cover is largely found on public land. Suburban Baltimore County has a unique role in maintaining forests on residential land, in close proximity to most of the county's population, with the greatest number of patches relative to area. For all of the regions we considered, large forest patches were distributed across multiple parcels and many types of ownership and land use. Working across parcel boundaries, and ownerships and land uses, has the potential to expand forest conservation and management, from urban to rural settings. Uniting forest management challenges and opportunities across urban and rural settings, and across parcel scales, holds promise for furthering these forest management goals. Experiences with forest conservation and management here will be relevant to other metropolitan areas in forested ecoregions of the United States that are also coping with the legacies of land use change and development over time.

Funding

This research was supported by the U.S. Department of Agriculture (USDA) Forest Service, Northern Research Station, agreement 17-JV11242308-056. The findings, opinions, and conclusions presented are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy

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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. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2025.128778.

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