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Squeezed from All Sides: Urbanization, Invasive Species, and Climate Change Threaten Riparian Forest Buffers

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Abstract: Streamside forests of urbanizing coastal regions lie at the nexus of global changes: rising sea levels, increasing storm surge, expanding urban development, and invasive species. To understand how these combined stressors affect forest conditions, we identified forest patches adjacent to urban land, analyzed adjacent land cover, modeled forest inundation, and sampled 100 sites across the Chesapeake Bay and Delaware Bay watersheds. We found that the majority of forest patches are adjacent to urban land and projected flooding will affect 8–19% of regional forested land. We observed non-native invasive plants in 94% of forest plots. Trees were predominantly native, but over half of shrub stems were invasive species and more than 80% of plots contained invasive woody vines. Disturbance of human origin was correlated with abundance of invasive trees. Signs of deer activity were common. Richness and number of growth forms of invasive plants were related to adjacent agricultural land cover. These data reveal that streamside forests are impacted by the interacting stressors of urbanization, climate change, and invasive species spread. Our results emphasize the importance of protection and restoration of forests in urban regions and point to the need for a social-ecological systems approach to improve their condition.

Keywords: forest patch; storm surge; sea level rise; urban ecology; plant community; disturbance; social-ecological system; invasive species; climate change; spatial analysis

1. Introduction

Forests in urbanizing coastal zones are undergoing unprecedented change as urbanization accelerates simultaneously with invasive species spread and climate change. Coastal ecosystems are vulnerable to global climate change as sea levels rise and storm surge events increase [1–4]. They are also at risk for increased urbanization and development pressures because many urban centers occur in coastal areas. Seventy-five percent of the world's largest cities—and 65% of the densest cities—are located in coastal zones [5], and population growth is projected to increase in coastal cities [6]. At the same time, cities are hotspots for introduction of non-native species [7]. Streamside forests of urbanizing coastal regions lie at the nexus of these global changes, yet the extent and potential impact of these combined stressors on riparian urban forests and on their ability to provide valuable water filtration and support for biodiversity is currently unknown. These forests are "squeezed" from all sides by adjacent urbanization on land, rising sea levels and storm surge, and from within by non-native invasive plants (Figure 1). Understanding relationships between urban riparian forests and the combined effects of urbanization, climate change, and invasive species requires a social-ecological approach.

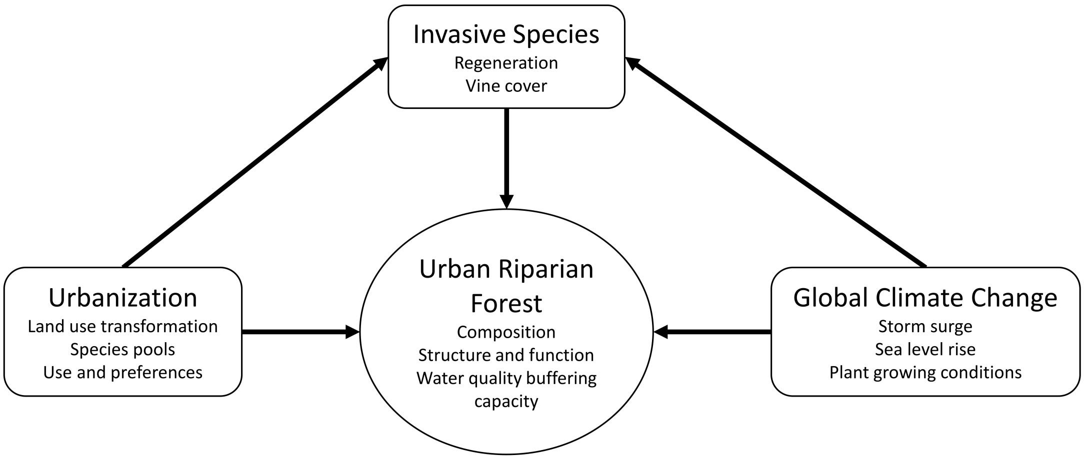

Figure 1. Conceptual model depicting urbanization, global climate change, and invasive species impacts on urban forest buffers along stream corridors. We propose that urban riparian buffers will experience shifts in species composition and subsequent ecological functions due to combined effects of sea level rise, urbanization, and invasive species, and, thus, are "squeezed from all sides". Anthropogenic factors are the ultimate driver of ecosystem change.

The structure, composition, and ecosystem functions of forest patches are affected by landscape-scale fragmentation, isolation, and adjacent land use change due to urban land use transformation [8,9], and also by parcel-scale human activities [10,11]. Management actions affecting these forests range from biodiversity conservation to lumber production, and also include actions based on social perceptions and motivations. Land owners or neighbors may choose to thin or cut forests to remove "messy" vegetation [12,13] or improve views of waterways. Riparian vegetation is constricted in urban areas by hardened shorelines, and by housing development situated as near as possible to valued water views. Proximity of the built environment to the water can prevent migration of buffering vegetation inland with sea level rise, leading to loss of needed nutrient capture capacity for urban and suburban runoff, as well as decreased habitat value. Reduction of riparian vegetation and connectivity between streams and floodplains can further exacerbate urbanization impacts on streams by reducing nutrient retention and flood water retention [14–16]. Both urban conditions and rising saline waters [17,18] affect species composition, which is an underlying determinant of forest health and function.

Predicted global sea level rise and storm surges will increase salinity in coastal urban surface waters, altering adjacent forest function and health. The effects of sea level rise may be compounded further by increased storm surges, salt water intrusion into groundwater and changes in sediment flow [19]. Sea level rise is a global trend with effects that vary widely on a regional level [20], and all levels of government are now developing strategies for climate change adaptation. Vegetation along urban and suburban shorelines is increasingly considered to be important for protective function in relation to storm surge, leading coastal cities to increase buffer vegetation for this purpose [21].

While horizontal stressors from urbanization and sea level rise impact these forests, urban biophysical conditions act as a filter on regional species pools [22] as non-native species are continually introduced into cities [23,24]. Top-down impacts on forest regeneration [25,26] and bottom-up alterations to soil processes [27–29] due to invasive plants make urban riparian forests especially vulnerable. Cities are centers of species introduction, some of which are or become invasive and may spread from cities into surrounding landscapes [30]. Fragmentation and loss of habitats due to urban land use transformation create high edge-to-interior ratios in urban forest patches [31], increasing the permeability of these forests to dispersal of invasive plants. Linear forest strips, such as buffers along waterways and roads, are particularly susceptible [32]. Invasive plant species can not only reduce native biodiversity and the resources available to wildlife, but in the case of invasive vines in urban and suburban forests, they can increase tree mortality and prevent forest regeneration [33], often in concert with high abundance of herbivores in urbanized regions where predators have been extirpated [34].

The goal of this study was to understand the extent of riparian buffer forests vulnerable to urbanization, invasive species, and sea level rise impacts (hereafter, "squeezed forests") that have the potential to alter ecosystem function and health. We conducted a spatial analysis to model the extent and location of these stressors in urban and suburban environments and identified forested areas of greatest vulnerability to urbanization pressures, sea level rise, and storm surge. Preliminary observations indicated that invasive plants are widespread in these forests, but existing records of invasive plant species abundance were not spatially contiguous. To understand the extent and impact of invasive plant pressure, we conducted field sampling of forest composition, forest structure, and local-scale human impacts.

This research addresses existing information gaps at the intersection of multiple large-scale causes of ecosystem change. We asked the following questions:

What is the spatial extent of forests squeezed by urban land use and potential loss to sea level rise and storm surge? Coastal areas of the eastern United States are affected by increasing urbanization, rising sea levels, and increasing inland impacts of storm surges. Estuarine and riverine forests that serve important buffer functions are threatened by both. We expected forests affected by these combined stressors to be common across the study area, and we expected that these forests would also be impacted by invasive plants.

Does non-native plant invasion vary with differences in landscape context and disturbance? Land use and land cover surrounding forest patches influences their composition in complex ways, including species introductions, isolation of populations in habitats, and local microclimate alteration. We expect plant communities of squeezed forests to exhibit effects of local human impacts, surrounding conditions, and land use and land cover adjacent to the forest patch, such as high rates of invasive plant cover and indicators of human use and human-caused ecological disturbance.

Study Area

The urbanized coastal mid-Atlantic region of the United States sits at the intersection of these major forces of ecological change. This segment of the Eastern Seaboard is home to more than 40 million people in a dense matrix of cities and towns stretching along the Atlantic coast between Virginia and New Jersey, including Philadelphia, Washington, Wilmington, Trenton, and Baltimore (Figure 2). The region has experienced a long-term trend of population growth. From 2000 to 2010 (the most recent census period), Delaware's population increased by 14.6% (114,334 people), Virginia's by 13% (922,509), Maryland's by 9% (477,066), Pennsylvania's by 3.4% (421,325), and New Jersey's by 4.5% (377,544 people) [35]. Population centers are clustered along the coastline, and urban and suburban development has increased in coastal areas at a faster pace than inland. Urban land use transformation in the United States is projected to result in loss of ca. 118,000 km^2 of forest by 2050, with states in this region already exhibiting the nation's highest rates of urbanization and one—New Jersey—to become more than 50% urban land [36].

The mid-Atlantic region also contains two large biologically and economically important estuarine systems: the Chesapeake and Delaware Bays. This study is focused on forest patches within the boundaries of the Chesapeake and Delaware Bay watersheds (Figures 2 and 3), which together drain an area of nearly ten million hectares. In the Chesapeake Bay watershed, one-third of urban development land use transformation in recent decades has resulted in forest loss, and the fastest-growing urban areas surrounded by forested land have experienced the most loss of forest to impervious surfaces [37].

Figure 2. The Northeastern United States "Megalopolis", as seen from space at night. Our study area incorporates municipalities in the watersheds of two major bays—the Delaware and the Chesapeake—and includes cities from Norfolk to Philadelphia. The Delmarva peninsula, which separates the two bays, extends below Baltimore in this photo toward Norfolk and is partially covered by a solar panel. Image credit: U.S. National Aeronautics and Space Administration (NASA), International Space Station.

Figure 3. Study area (light gray land area) and location (gray circles) of sampled municipalities. The study region encompasses the watersheds of the Chesapeake and Delaware Bays.

This region is also particularly vulnerable to climate change. On the Delmarva Peninsula, which sits between the Chesapeake Bay and Delaware Bay and is shared by the states of Delaware, Maryland, and Virginia, sea level rise is compounded by land subsidence. The peninsula has been sinking at the rate of 1.3 mm per year for the last 1000 to 2000 years [38]. Consequently, while global sea levels have risen 4–8 inches in the last century, the peninsula's relative sea level rise (including land subsidence) was approximately 12 inches and projections are that the effective sea level rise may be up to an additional 2 to 5 feet in the next 100 years [39].

2. Materials and Methods

To understand the degree to which riparian forests are vulnerable to interactive effects of these combined stressors, we examined riparian forest patches likely to be affected by storm surge and sea level rise along a gradient of city size. We conducted analyses at landscape, forest patch, and plot scales. First, we used geospatial data to estimate the extent of forest patches likely to be affected by multiple stressors under varying scenarios of sea level rise at a regional scale. We then selected and sampled 100 sites that would be affected by storm surge under the most conservative model. In these sites, we examined vegetation and indicators of disturbance at a plot scale.

2.1. Squeeze Modeling

To assess the potential extent of urban riparian forests vulnerable to simultaneous stresses of urbanization, sea level rise, and storm surge in this region, we integrated national land use and land cover data with inundation risk modeling.

2.1.1. Modeling Urbanization and Forest Extent

ESRI ArcGIS® 10.5.1 software [40] was used to store and analyze over 350 GB of geospatial data. Using the Watershed Boundary Dataset [41], we delineated watersheds draining into Delaware Bay and the Chesapeake Bay for geospatial analyses, comprising a total study area of 9,829,678 ha. We used the U.S. National Landcover Database (NLCD) 2011 land cover product [42] to identify forest patches adjacent to urban development. Selected forest patches were located within 500 m of areas classified by NLCD (2011) as Developed Medium Intensity (impervious surface cover 50–79%, commonly including medium to high density single-family housing units) or Developed High Intensity (impervious surface cover 80–100%, commonly including apartment complexes, row houses and commercial/industrial areas). Minimum forest patch size was set at 0.1 ha (0.25 ac), following [43]; for context, this is also the size of an average American suburban residential yard. Forest type classes included Deciduous Forest, Evergreen Forest, Mixed Forest, and Woody Wetlands. From this analysis, we derived the number, size, and public v. private ownership of forest patches. We also derived land cover type within a 500 m buffer of sites selected for ground sampling, and proportional and absolute perimeter adjoining land cover types of each forest patch. Additional land cover types included Cultivated Crops, Developed Open Space, Hay/Pasture, Emergent Herbaceous vegetation, Shrub/Scrub vegetation, and Barren Land (NLCD 2011).

2.1.2. Modeling Sea Level Rise and Storm Surge Vulnerability

To model the combined stressors of sea level rise and storm surge, we synthesized four datasets: a Digital Elevation Model (DEM) of the area, storm surge surface models, sea level rise surface models, and the National Hydrography Dataset. To estimate storm surge, we merged Sea, Lake, and Overland Surges from Hurricanes (SLOSH) storm surface models for New York, Delaware Bay, and Chesapeake Bay basins [44–46]. Ordinary kriging was used to extend the storm surge surface inland, and 10 m rasters estimating storm surges for category 1, 2, and 4 hurricane events were generated. Sea level rise (SLR) was estimated from a DEM mosaic of the NOAA Coastal Services Center Coastal Inundation Digital Elevation Model [47] and the US Geological Survey standard DEM 1/9 arc-second product [48] resampled to 10 m using cubic convolution. Sea level rise was estimated for 0.0 m, 0.6 m, and 1.8 m sea level rise scenarios. By combining these layers, 9 storm surge-sea level rise surfaces were generated (Cat 1, 2, and 4 storms) x (0.0 m, 0.6 m, and 1.8 m SLR).

Initial inundation extent was estimated by subtracting DEM values from storm surge/sea level rise surfaces. This initial output was evaluated for connectivity (inundation) using an 8 sided neighborhood rule and connected cells were extracted. Area water features identified in the National Hydrography Dataset [49] were dissolved and converted to a 10 m raster. This layer and areas of land not typically inundated derived from the DEM hydrologic break lines were combined to form a mask to extract connected cells. Inundated areas with less than 95% confidence were removed to form the final inundation extents.

We note that the resulting model is a "gentle flooding model" (water rises and covers)—no effort was made to model backpressure effects—and inundation is shown as it would appear during the mean high tides (excludes wind driven tides). We also did not account for erosion/deposition, subsidence/uplift, future changes in hydrodynamics, or preexisting conditions such as soil moisture and river input.

2.2. Field Rapid Assessment of Stressors and Forest Conditions

To determine the extent and intensity of invasive plant pressure on forests vulnerable to urbanization and flooding due to storm surge and sea level rise, we conducted a rapid field assessment. This assessment also documented evidence of human activity and non-human ecological disturbances.

2.2.1. Selection and Location of Sampling Points

We selected 20 municipalities representing the range of municipality sizes occurring in the study region (Figure 3 and Table A1) and located 5 points in each municipality (total: 100 sites) for field-based measurement of invasive plant species, vegetation composition and structure, and indicators of impact from human management and use. Selected sites were located on public lands to facilitate access for observation. To identify areas of greatest potential vulnerability to combined stressors, forest patches were selected based on adjacent urbanization and potential inundation modeling. Adjacent urbanization was defined using NLCD 2011 [42] as described in Section 2.1.1. above. Sampling points were located within the boundary of the most conservative scenario for storm surge and sea level rise: Category 1 hurricane storm surge with no (zero) sea level rise; these locations would be inundated under all scenarios. Center points of sampling plots were randomly assigned within these patches, including additional points for use when encountering barriers preventing access to a coordinate. Field technicians located sampling points using GPS. Where the location of a coordinate in the field was not entirely inside a forest patch due to error inherent in remote sensing and/or change in patch boundaries, plot center was relocated to the interior of the forest patch.

2.2.2. Field Sampling: Vegetation

Circular plots of 400 m^2 (11.3 m radius) were established around the randomized coordinates. A laser hypsometer was used to determine plot boundary. In each plot, all trees > 2.5 cm diameter were identified to species. Greatest degree of vine coverage on trees, dominant vine species, dominant herbaceous species, and indicators of disturbance were recorded for the entire plot. Degree of vine coverage was based on the Schumaker vine invasion index [50]. Categories of coverage were: 0: no lianas climbing trees, 1: vines at the base of tree bole, 2: vines covering tree bole, 3: partial canopy coverage, and 4: complete canopy coverage. In a 20 m^2 circular subplot at the center of each plot, ground layer cover of all species was visually estimated using 1/8 radial increments. Within subplots, individual trees of all size classes (including seedlings < 1m in height and saplings > 1m in height and < 2.5 cm DBH) and all shrub stems emerging from the ground were counted and identified. Species were categorized as native or non-native to the mid-Atlantic region following the USDA PLANTS Database [51]. Non-native species were categorized as invasive if they appeared on a state invasive plant list of one of the states in the study region [52–56]. All invasive species were non-native. Field identification followed [55,57–60]; taxonomy follows USDA PLANTS Database [51].

2.2.3. Field Sampling: Disturbance Indicators

Indicators of human and non-human ecological disturbance were developed from regional and urban assessments of environmental impact and were designed to be compatible with these measures for cross-comparability. These included assessments utilized in rural riparian and forest systems [61–64], assessments used by urban land managers [65–68], studies examining human impacts on urban forest systems [10,69], and indicators of non-human forest disturbance [70,71]. Evidence of human activity included vegetation manipulation such as cutting or planting; dumping or accumulation of household waste; digging, shoreline alteration, and earth moving; trails, roads, and trampling; recreational equipment and camping; fencing; and building. Non-human disturbances included canopy gaps due to fallen trees and high levels of herbivory. High abundance of white-tailed deer (*Odocoileus virginicus*) in the region can affect forest regeneration [34,72–75], so signs of deer (e.g., tracks, browse, scat) were also recorded.

2.3. Statistical Analysis

Statistical analyses were performed in R version 3.6.1 (R Core Team, 2016). All tests for significance are reported at the $\alpha = 0.05$ critical value, and, in a few cases, the $\alpha < 0.10$ critical value is reported to identify potential trends. Pearson correlation analysis was used to assess whether the species richness of invasive vines present correlated with the intensity of vine coverage (trunk and canopy cover) across forest patches. To assess the influence of local human activities on invasive plant species, we performed bivariate linear regression analysis between the abundance of invasive trees, saplings, seedlings, shrubs, or total species and the observable signs of natural and human disturbance within forest plots. To assess human influences on invasive plant abundance across spatial scales, we performed pairwise linear regression analysis between the richness of invasive plants or total number of invasive plant species by growth form (i.e., tree, shrub, vine, forb, graminoid) and (1) the proportion of urban, agricultural, and forest land use/land cover within 500 m of the forest plot center, (2) the proportion of urban, agricultural, and forest land use/land cover adjacent to the forest patch (i.e., along forest perimeter), and (3) the municipal population size for each city. Finally, we assessed the relationship between total municipal population for each city and (1) the richness of invasive plants, (2) the total number of invasive plant species by growth form, and (3) the abundance of invasive trees, saplings, seedlings, or shrubs and the total municipal population for each city using linear regression analysis.

3. Results

3.1. Spatial Extent

The results of this analysis reveal that many forest patches in the study area are vulnerable to combined stressors, and that these vulnerable forests comprise a significant proportion of the forested area in this urbanized region. The watersheds of the Chesapeake and Delaware Bays contained 443,968 forest patches greater than 0.1 ha (0.25 ac) in size, covering an area of 3,292,290 ha (12,711 mi^2), 41% of the land surface area of the study region (Table 1). They ranged in size from 0.6 to 370,719 ha, with a mean area of 74 ha but a median of only 1.8 ha.

Most forest patches in the region (280,275 patches; 63%) were bordered by high- or medium-density urban development. Forest patches adjacent to urban development spanned the entire range of forest patch size in the region and comprised 92% of forested land.

Under the most-likely near-term future scenario, in which a Category 1 hurricane makes landfall in the study area, storm surge would affect 33,443 (8%) of the region's urban-adjacent forest patches and inundate 5% of regional forest land area (Figure 4). With the larger storm surge of a Category 2 hurricane, 10% of regional forest patches would experience flooding, and 9% of the regional forest area (3,060,297 ha) would be inundated.

Table 1. Proportional cover by land cover class in the Chesapeake and Delaware Bay watersheds, excluding open water. Forest land cover classes include deciduous, evergreen, mixed, and woody wetlands.

Land Cover Type	Area (ha)	%
Forest	3,292,290	41.4%
Cultivated Crops	1,338,872	16.8%
Developed, Open Space	936,933	11.8%
Hay/Pasture	837,969	10.5%
Developed, Low Intensity	506,997	6.4%
Developed, Medium and High Intensity	361,724	4.5%
Emergent Herbaceous Wetlands	301,778	3.8%
Shrub/Scrub	284,936	3.6%
Herbaceous	59,406	0.7%
Barren Land	40,217	0.5%
Total	7,961,121	100%

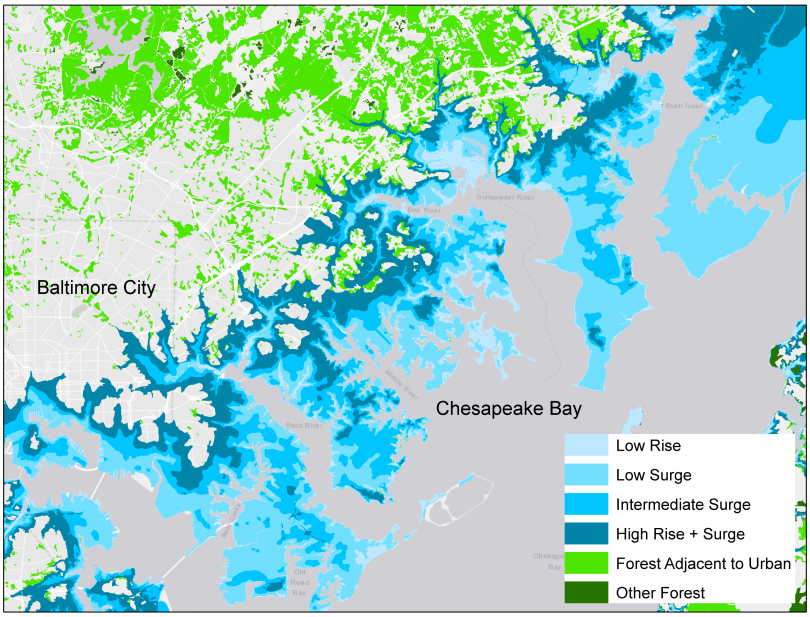

Figure 4. Inundation modeling under scenarios of storm surge and sea level rise. Darker blues indicate more extreme scenarios. Low Rise: 0.6 m sea level rise (SLR); Low Surge: Category 1 hurricane storm surge (SS); Intermediate Surge: Category 2 SS; High Rise + Surge: 1.8 m SLR with Category 4 SLR.

Under the lower sea level rise scenario without storm surge, 21,170 urban-adjacent forest patches would lose area to the rising sea. The flooded area (602,478 ha) would comprise 2% of the region's forests. Under the maximum sea level rise and storm surge parameters (6 ft sea level rise combined with Category 4 hurricane storm surge), 14% of regional forest patches would be affected, and 19% of regional forest land (6,169,628 ha, or 23,821 mi^2) is projected to go underwater.

3.2. Plant Community Composition

In forests squeezed by urbanization and sea level rise, patterns of species richness and composition differed among plant growth forms and forest layers. The forest layers with the most invasive plants were the shrub layer (where invasive plants were present in 61% of forests) and woody climbing vines (present in 83% of forests). We identified 92 species of trees including 88 species of trees > 2.5 cm DBH, 39 species of tree saplings (> 1 m in height and < 2.5 cm DBH), and 69 species of tree seedlings (< 1 m in height); 28 species of vines, 72 species of forbs, 10 graminoids, and 42 shrub species. The majority of individual trees (94%), tree saplings (92%), and tree seedlings (90%) were native species (Figure A1), whereas over half of the shrubs found across the forests were invasive species (52%;

Figure 5; Figure A1). We observed at least one invasive plant species in almost every forest plot (94% of forest plots; Figure 6).

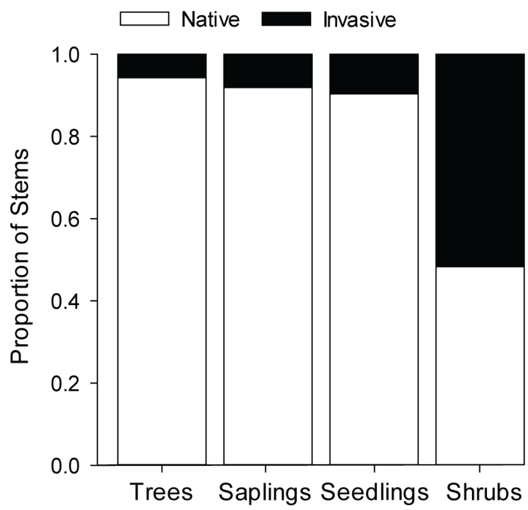

Figure 5. The proportional abundance of total woody plant stems by growth form belonging to non-native invasive species (black) and native species (white) across 100 forest patches in the Chesapeake and Delaware Bay watersheds of the mid-Atlantic coast of the United States.

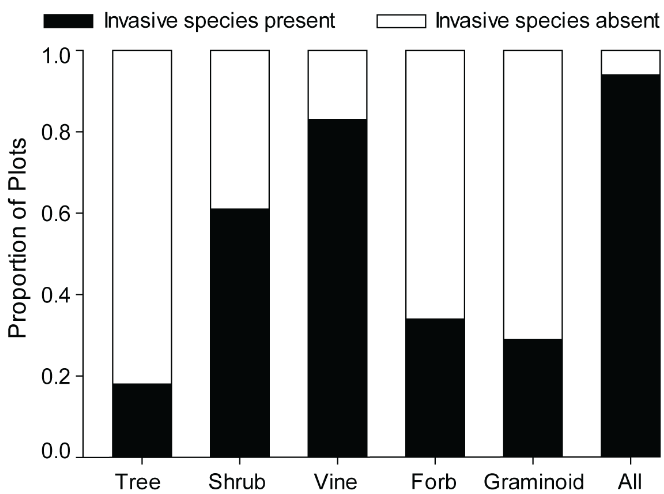

Figure 6. The proportion of plots containing invasive plants across plant growth forms (trees, shrubs, vines, forbs, and graminoids) and the total number of plots containing invasive plants of any growth form.

3.2.1. Trees

While the majority of canopy trees > 2.5 cm DBH were native, the most abundant non-native trees encountered in both the canopy and in recruiting size classes would be familiar to managers of urban forests of the region (Figure A1). These include widely planted street trees and ornamental introductions from temperate Asia, among them the cosmopolitan tree-of-heaven (*Ailanthus altissima*), regionally spreading ornamental hybrid Callery pear (*Pyrus calleryana*), Norway maple (*Acer platanoides*), mimosa (*Albizia julibrissin*), white mulberry (*Morus alba*), bird cherry (*Prunus avium*), and princess tree (*Paulownia tomentosa*). All non-native trees sampled were listed as invasive plants in one or more states in the study region, with the exception of *Ginkgo biloba*.

The most frequently observed mature tree species were native (*Acer rubrum*, 50% of plots; *Prunus serotina*, 41% of plots). The most abundant tree (*Acer rubrum*, 335 stems across all plots) was native (Figure A1). Invasive trees were found in 18% of forest plots and the most frequent invasive tree was *Ailanthus altissima* (8% of plots).

3.2.2. Tree Seedlings and Saplings

The most frequently observed canopy tree saplings (*Liquidambar styraciflua* and *Prunus serotina*, found in 5% of plots) and canopy tree seedlings (*Prunus serotina*, 27% of plots; *Acer rubrum*, 24% of plots) were native species. The most abundant sapling (*Ostrya virginiana*, 15 stems across all plots) and seedling (*Acer rubrum*, 385 stems across all plots) were also native species (Figure A1). However, we found that not all forest plots contained native saplings; 77% had seedlings and only 30% had saplings of native tree species. Almost one quarter (24%) of plots contained invasive trees, yet regeneration and recruitment of invasive trees was observed in fewer forest patches (non-native seedlings: 18% of plots; non-native saplings: 5% of plots).

3.2.3. Shrubs

Invasive shrubs occurred in 61% of forest plots. The shrub layer of "squeezed" forests contained an assortment of regionally common invasive species introduced from temperate climate zones of Europe and Asia. These included the shrub honeysuckles Amur honeysuckle (*Lonicera maackii*, 416 total stems across all plots) and Morrow's honeysuckle (*Lonicera morrowii*), privets (*Ligustrum sinense* and *L. vulgaris*), multiflora rose (*Rosa multiflora*), Japanese knotweed (*Fallopia japonica*), autumn olive (*Elaeagnus umbellata*), wineberry (*Rubus phoenicolasius*), and burning bush (*Euonymus alatus*), in order of rank abundance (Figure A1). The most frequently encountered shrub, *Rosa multiflora* (found in 33% of plots), was a non-native, invasive species. However, the second most frequently encountered shrub species, *Lindera benzoin* and *Viburnum dentatum* (found in 18% of plots), were native. More than two-thirds (78%) of the invasive woody plants identified were invasive shrub species.

3.2.4. Vines

The most common invasive plants were vines; invasive woody vines were found in 83% of forest plots. Japanese honeysuckle (*Lonicera japonica*) was the most frequent of these (54% of plots) followed by *Hedera helix* (33% of plots), *Celastrus orbiculatus* (28% of plots), and *Ampelopsis brevipedunculata* (20% of plots). Other vine species were found in few plots (1–7% of plots). Most forest patches (81%) had woody vines growing on the trees, and two-thirds of plots (66%) had vines covering entire tree trunks and covering a quarter or more of tree canopies (Figure 7). There was a significant positive correlation between the species richness of invasive vines present and the degree of vine coverage on trees ($R = 0.31$, $p = 0.002$).

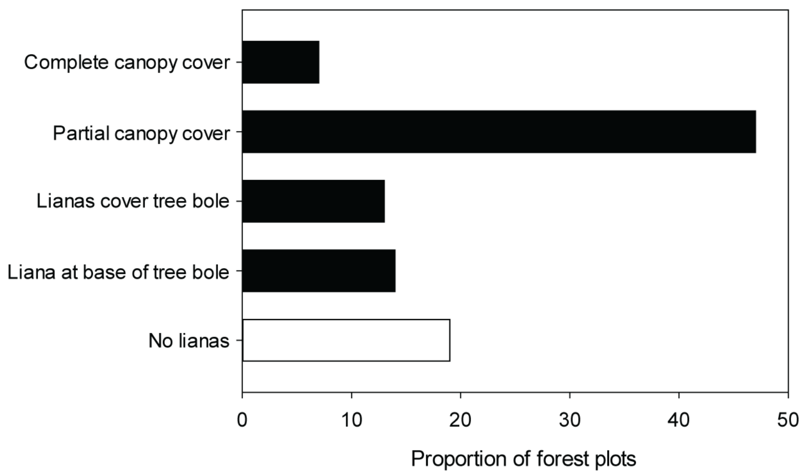

Figure 7. Proportion of forest plots by degree of maximum woody vine cover on trees. Forest plots with no vines are shown in white, and plots with vines are shown in black.

3.2.5. Forbs and Graminoids

Invasive forbs and graminoids were present in approximately one-third of forest plots (29% and 34% of plots, respectively; Figure A1). *Microstegium vimineum* (Japanese stilt grass) and *Phragmites australis* (common reed) were the most frequent invasive graminoids (23% and 7% of plots, respectively) and *Glechoma hederacea* (ground-ivy) and *Alliaria petiolata* (garlic mustard) were the most frequent invasive forbs (13% and 10% of plots, respectively).

3.3. *Effects of Landscape Context and Disturbance*

The potential for human-derived impacts to influence non-native plant invasion varies by spatial scale. Within each forest plot, we assessed we assessed presence or absence of signs of natural and human-caused disturbances (Table 2). The most frequent indicators of disturbance were human-derived, with visible signs of human activity occurring in 77% of the forest plots (Figure 8). The most frequent signs of human disturbance were vegetation manipulation (e.g., mowing), dumping, and garbage (Table 2), each of which occurred in greater than 60% of plots. Trails were encountered in 32% of plots. Disturbances not necessarily of human origin included canopy gaps caused by tree fall (29% of plots), erosion (4%), and fire (<1%). Signs of deer herbivory were observed in 46% of plots. While human-initiated ecological disturbances were common across our forest sites, we found no relationship between the number of different human disturbance types observed in a plot and the abundance of invasive saplings, seedlings, or shrubs, or total invasive woody plants. However, we found a significant positive relationship between the abundance of invasive trees and the number of visible signs of human disturbance in each forest plot ($r^2 = 0.14$, $p < 0.001$).

Table 2. Frequency of observed disturbance types.

Disturbance Category	Proportion of Sites
Vegetation manipulation	64
Dumping	63
Garbage	62
Deer signs [1]	46
Trail	32
Canopy gap due to fallen canopy tree	29
Other human activity	18
Gully erosion	15
Digging / Earth moving	13
Fencing	13
Trampling	11
Road	9
Recreational equipment	5
Building	4
Camping	3
None	3
Fire	2
Shoreline alteration [2]	2
Livestock grazing	1

[1] Deer signs included scat, browse, hoofprints, and browse line. [2] Shoreline alterations included riprap/armoring, bulkhead, and solid fill pier.

Surrounding land use/land cover within 500 m of the center of our forest plots provides an indication of local landscape influences. Although weak, we found significant positive relationships between the proportion of the area surrounding each forest plot that was in agriculture and the richness of invasive plants ($r^2 = 0.05$, $p = 0.03$) and the total number of growth forms of invasive plants per plot ($r^2 = 0.05$, $p = 0.02$; Figure 9). We found no relationships between differences in the proportion of forest or urban area within this radius and invasive plants (richness or number of growth forms); all plots had forest adjacent. All plots were located in patches adjacent to urban land, and 94% of plots had urban land use within 500 m of the sampling point.

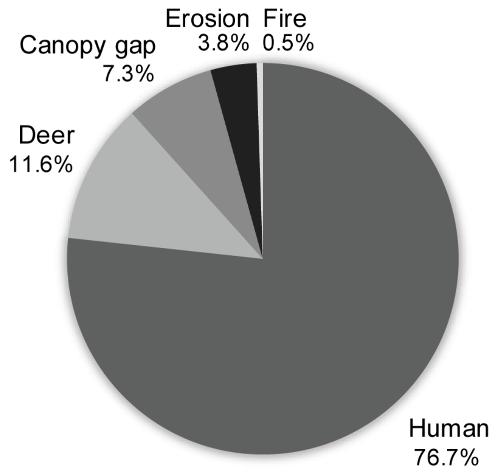

Figure 8. Frequency of observed disturbance by type. Most observed disturbance was of human origin, followed by evidence of deer browsing; canopy gaps due to tree fall; soil erosion; and fire.

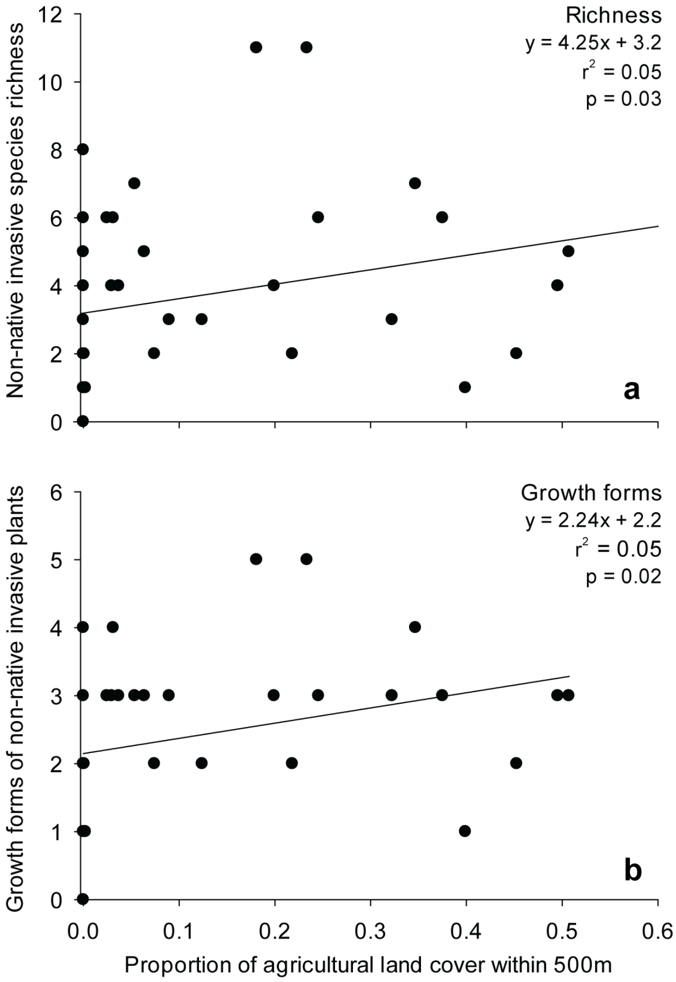

Figure 9. The (**a**) invasive plant species richness in each forest plot and (**b**) total number of growth forms of invasive plant species in each forest plot as a function of the proportion of agricultural land cover within 500 m of plot center. A greater diversity of growth forms indicates presence of invasive plants in multiple forest layers (i.e., herbaceous, shrub, tree, vine).

At the scale of the whole forest patch, land use/land cover adjacent to a forest patch (i.e., along the perimeter of the forest) had similar patterns in relation to invasive plants. The proportion of agricultural land cover adjacent to the forest patch had a significant positive relationship with the richness of invasive plants ($r^2 = 0.12$, $p < 0.001$) and number of growth forms of invasive plants ($r^2 = 0.08$, $p < 0.01$; Figure 10). We found no relationship between proportion of adjacent forest or urban development and invasive plants (richness or number of growth forms).

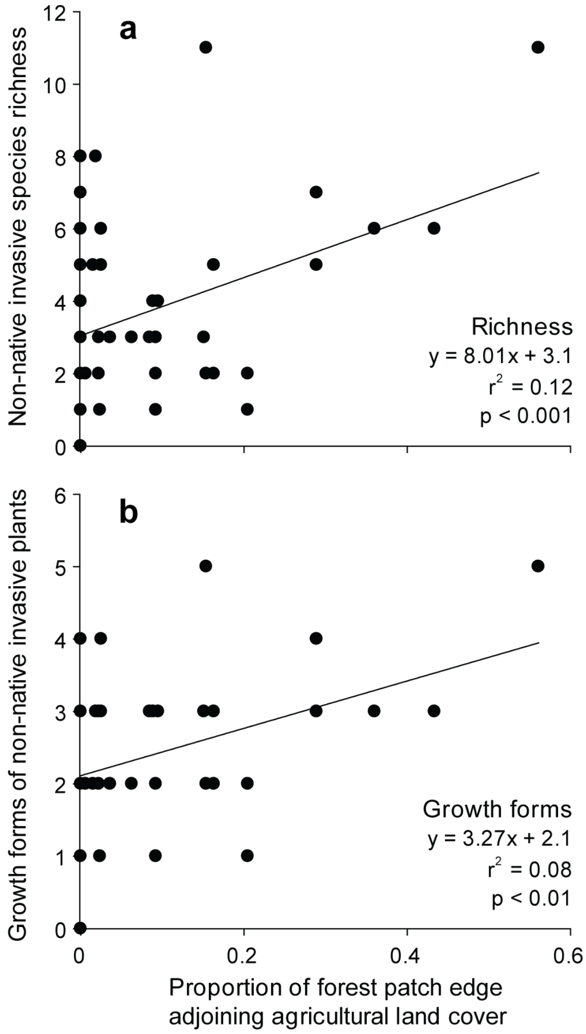

Figure 10. The (**a**) invasive plant species richness in each forest plot and (**b**) total number of growth forms of invasive plant species in each forest plot as a function of the proportion of the forest patch edge adjacent to agricultural land cover.

At the metropolitan scale, we found no significant relationships between municipal population size and the richness of invasive plants or total number of invasive plant species by growth form. We found a weak positive association between the total municipal population and the abundance of invasive trees ($r^2 = 0.15$, $p = 0.09$). However, this pattern was driven by one forest in Philadelphia that contained multiple invasive trees, such as *Acer platanoides*, *Ailanthus altissima*, and *Morus alba*. There were no significant relationships between municipal population size and the abundance of invasive saplings, seedlings, or shrubs.

4. Discussion

This research provides a first essential step in understanding the extent to which urban riparian forests are vulnerable to three significant stressors (urbanization, plant invasion, and sea level rise) that ultimately influence ecosystem health and function.

4.1. Spatial Patterns

Our analysis reveals that forests are threatened by urbanization and sea level rise throughout the densely populated central mid-Atlantic coast of the United States. In the Chesapeake Bay and Delaware Bay watersheds, nearly two-thirds of forest patches are bordered by medium- or high-density urban development. Under the most conservative climate change scenario—no sea level rise and a Category 1 hurricane—8% of the region's forests would be inundated by storm surge. Under the most likely projection for sea level rise, 2% of the region's forests would be permanently flooded, whereas under the maximum sea level rise and hurricane projection, nearly a fifth of regional forest land would flood. These results indicate that a large proportion of the region's forests adjacent to urban development are vulnerable to changes in sea level and increasing storm severity. These low-lying forests are relied upon to support biodiversity and buffer land-based pollution from harming aquatic life in these highly productive and economically important bays.

4.2. Forest Condition

Forests threatened by rising waters and urbanization are also affected by non-native plant invasion, as indicated by our field sampling of 100 forest sites across the study region. More than two-thirds of the invasive plants in these forests were shrubs, and invasive vines were found in more than 80% of sampled sites. The health of these forests is compromised by these non-native woody vines [33], which we observed both as dense ground layer cover (as in the case of *Lonicera japonica*) and covering tree canopies (e.g., *Celastrus orbiculatus* and *Ampelopsis brevipedunculata)*. Two-thirds of sampled forests had invasive woody vines in the tree canopy. These results suggest that urban forests threatened by sea level rise and storm surge are also experiencing internal pressures from non-native plant invasion.

The exception to the pattern of invasive plant dominance was the canopy tree layer of the forest, which was dominated by native species. The most abundant tree species are a regionally common set of early pioneer species that colonize following ecological disturbance, indicating that these sites have been colonized relatively recently. Further investigation could reveal whether there are regional patterns of historic land use change influencing the current condition of these forests. Interestingly, many of the most common trees were species typical of uplands rather than wetland or riparian zones. This could indicate effects of flashy hydrology typical of urban environments and runoff from impervious surfaces, which erode streams and can restrict access of floodwaters to floodplains in a cycle of deepening incision [76]. Flood plain dissipation of storm flows and infiltration of both water and pollutants is an important buffering function of riparian streams that may be compromised.

4.3. Drivers of Forest Conditions

Forests threatened by rising waters and urbanization are also subject to more direct human-caused ecological disturbance, which we observed in more than three quarters of sites sampled. Much of this disturbance involved manipulation of vegetation such as mowing, pruning, and tree cutting; the other most common disturbance was dumping of household and yard waste. Abundance of non-native trees was correlated with these types of human disturbances.

Forest patch configuration, although not explored here, may also be an important driver of human-caused ecological disturbance and vulnerability to invasive plant species [77]. Signs of high abundance of white-tailed deer (*Odocoileus virginicus*) were also frequently observed. Populations of this important browsing herbivore are currently many times larger than historical estimates due to predator extirpation and increase in favorable forest edge habitats [78], and many urban deer populations have lost human avoidance behavior.

One limitation of this study is the fact of a limited observation window over time and space; our observations here are likely influenced by processes occurring across temporal and spatial scales that are not directly considered [79,80]. For example, legacies of species introduction by agriculture are a little-considered but potentially very important driver of urban plant community composition.

Urbanization often transforms agricultural lands to urban land use as cities grow beyond their starting points into surrounding supporting land uses. We found weak associations between adjacent agriculture and both the species richness and variety of growth forms of non-native invasive plants. Influence of land use history and the scale of landscape change processes on ecosystem change are increasingly recognized to be important and are likely to be at play here. Our focus in this study is to draw attention to the interacting stressors on streamside forests but gaining a better understanding of ecological drivers in future work will necessitate an explicit treatment of temporal and spatial scale.

5. Conclusions

Here, we have established the spatial extent of forests currently under broad-scale environmental pressures in a major urban region that spans two large and productive estuarine bays, and revealed the role of invasive plants in these forests. By encompassing three major sources of ecosystem change, we provide new insight into how the interaction of these stressors might affect the function of urban riparian buffers, and potential for change. Our results emphasize the importance of protection and restoration of forests in urban regions and point to areas for future work.

Both urbanization pressures and human-caused ecological disturbances are most appropriately understood as part of a social-ecological system. Here, field data from publicly owned forest patches demonstrate impacts of multiple stressors. This approach could be extended to include forests under private ownership to better understand the influence of fine-scale management decision making. Collaboration with social scientists to identify social drivers of decision making at the scale of individual properties that affect buffer function and perception of buffer management, combined with identification of appropriate conservation and management targets for urban riparian buffer forests, would speed development of new approaches to buffer edge management. The integration of environmental and social benefits with improved buffer condition and function can maximize function for habitat and water quality while meeting the needs of urban communities.

In highly urban regions, remnant, regenerating, and emerging riparian ecosystems are simultaneously subject to the multiple stressors of rising seas, increasingly strong storms, urban development, and invasive species spread. While inland development limits their extent and alters their condition, sea level rise squeezes these forest patches from the shore, and invasive plants cover forest canopies and suppress tree regeneration. Where pressures combine, there is a greater likelihood of loss of habitat and water quality buffer functions but also greater opportunity and potential for effective management to mitigate the loss.

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Appendix A

Table A1. Size, population, density and Metropolitan Statistical Area of sampled municipalities.

Municipality	State	Population	Area (km^2)	Population Density (/km^2)	Metropolitan Statistical Area (MSA)	MSA Population
Philadelphia	PA	1,526,006	370	4129	Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	6,011,545
Washington	DC	601,723	177	3400	Washington-Arlington-Alexandria, DC-VA-MD-WV	5,695,369
Norfolk	VA	242,803	250	972	VA Beach-Norfolk-Newport News, VA-NC	1,685,610
Newport News	VA	180,719	310	583	VA Beach-Norfolk-Newport News, VA-NC	1,685,610
Toms River	NJ	88,791	106	840	New York-Northern NJ-Long Island, NY-NJ-PA	19,039,570
Suffolk	VA	84,585	1111	76	VA Beach-Norfolk-Newport News, VA-NC	1,685,610
Wilmington	DE	70,851	44	1615	Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	6,011,545
New Brunswick	NJ	55,181	15	3703	New York-Northern NJ-Long Island, NY-NJ-PA	19,039,570
Essex	MD	39,262	31	1275	Baltimore-Towson, MD	2,738,814
Dover	DE	36,047	61	593	Dover, DE	166,656
Millville	NJ	28,400	115	246	Vineland-Millville-Bridgeton, NJ	157,291
Bridgeton	NJ	25,349	17	1507	Vineland-Millville-Bridgeton, NJ	157,291
Pleasantville	NJ	20,249	19	1073	Atlantic City-Hammonton, NJ	273,331
Joppatowne	MD	12,616	19	659	Baltimore-Towson, MD	2,738,814
Neabsco	VA	12,068	13	960	Washington-Arlington-Alexandria, DC-VA-MD-WV	5,695,369
Ocean City	NJ	11,701	30	391	Ocean City, NJ	97,616
Smyrna	DE	10,023	16	644	Dover, DE	166,656
Edgemere	MD	8669	53	163	Baltimore-Towson, MD	2,738,814
New Castle	DE	5285	9	579	Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	6,011,545
Croom	MD	2631	92	29	Washington-Arlington-Alexandria, DC-VA-MD-WV	5,695,369

Table A2. Forb and graminoid species found across the 100 forest sites. Non-native species listed as invasive in one or more states within the study area are indicated in red.

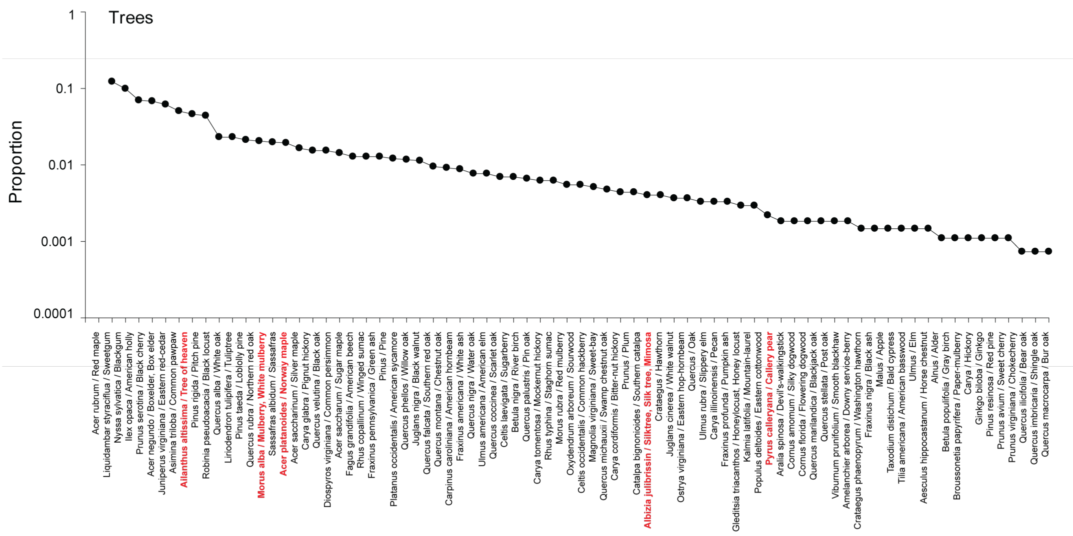
Scientific Name	Common Name	Growth Form
Achillea millefolium	Yarrow	Forb
Ageratina altissima	White snakeroot	Forb
Alliaria petiolata	Garlic mustard	Forb
Allium vineale	Vineyard onion	Forb
Ambrosia artemisiifolia	Annual ragweed	Forb
Anagallis arvensis	Scarlet pimpernel	Forb
Apocynum	Dogbane	Forb
Apocynum cannabinum	Indian hemp	Forb
Arisaema triphyllum	Jack-in-the-pulpit	Forb
Artemisia vulgaris	Common wormwood	Forb
Asarum canadense	Canadian wild ginger	Forb
Bidens	Beggarticks	Forb
Boehmeria	False nettle	Forb
Botrychium virginianum	Rattlesnake fern	Forb
Chaerophyllum tainturieri	Hairy-fruit chervil	Forb
Circaea lutetiana	Enchanter's nightshade	Forb
Commelina communis	Asiatic dayflower	Forb
Convallaria majalis	European lily of the valley	Forb
Conyza canadensis	Canadian horseweed	Forb
Diodia teres	Rough buttonweed	Forb
Duchesnea indica	Mock strawberry	Forb

Table A2. *Cont.*

Scientific Name	Common Name	Growth Form
Eclipta prostrata	False daisy	Forb
Erechtites hieraciifolius	American burnweed	Forb
Erigeron annuus	Annual fleabane	Forb
Eurybia	Aster	Forb
Euthamia graminifolia	Flat-top goldentop	Forb
Fabaceae sp	Legume	Forb
Froelichia gracillis	Slender snakecotton	Forb
Geum canadense	White avens	Forb
Glechoma hederacea	Ground ivy	Forb
Helenium autumnale	Common sneezeweed	Forb
Heterotheca subaxillaris	Camphorweed	Forb
Impatiens capensis	Spotted jewelweed	Forb
Lespedeza cuneata	Chinese bush-clover	Forb
Lobelia cardinalis	Cardinal flower	Forb
Lycopodium	Clubmoss	Forb
Lysimachia nummularia	Moneywort	Forb
Maianthemum canadense	Mayflower	Forb
Matteuccia struthiopteris	Ostrich fern	Forb
Oenothera biennis	Small flowered evening primrose	Forb
Onoclea sensibilis	Sensitive fern	Forb
Osmorhiza longistylis	Aniseroot	Forb
Osmunda cinnamomea	Cinnamon fern	Forb
Oxalis corniculata	Creeping wood sorrel	Forb
Oxalis stricta	Upright yellow wood sorrel	Forb
Phytolacca americana	Pokeweed	Forb
Pilea pumila	Canadian clearweed	Forb
Plantago	Plantain	Forb
Plantago lanceolata	English plantain	Forb
Plantago rugelii	Black-seed plantain	Forb
Podophyllum peltatum	May-apple	Forb
Polygonatum	Solomon's seal	Forb
Polygonatum biflorum	King Solomon's seal	Forb
Polygonum cuspidatum	Japanese knotweed	Forb
Polygonum persicaria	Spotted ladysthumb	Forb
Polygonum virginianum	Jumpseed	Forb
Polystichum acrostichoides	Christmas fern	Forb
Potentilla canadensis	Dwarf cinquefoil	Forb
Rudbeckia laciniata	Green-head coneflower	Forb
Saururus cernuus	Lizard's tail	Forb
Smallanthus uvedalius	Hairy leafcup	Forb
Solanum carolinense	Carolina horse nettle	Forb
Solidago	Goldenrod	Forb
Symphyotrichum racemosum	Fragile-stem American-aster	Forb
Symplocarpus foetidus	Skunk cabbage	Forb
Taraxacum officinale	Common dandelion	Forb
Thelypteris noveboracensis	New York fern	Forb
Veronica arvensis	Speedwell	Forb
Viola sororia	Common blue violet	Forb
Yucca	Yucca	Forb
Ammophila breviligulata	American beach grass	Graminoid
Carex	Sedge	Graminoid
Cyperus esculentus	Nut grass	Graminoid
Dichanthelium clandestinum	Deer-tongue rosette grass	Graminoid
Digitaria	Crabgrass	Graminoid
Lolium perenne	Perennial rye grass	Graminoid
Microstegium vimineum	Japanese stilt grass	Graminoid
Phragmites australis	Common reed	Graminoid
Poa pratensis	Kentucky bluegrass	Graminoid
Poaceae	Grass	Graminoid

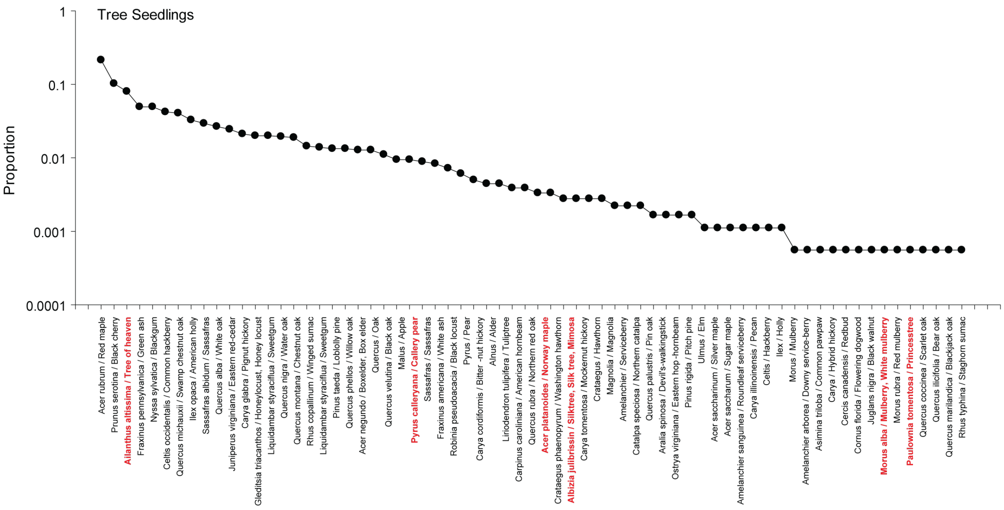
Table A2. *Cont.*

Scientific Name	Common Name	Growth Form
Ampelopsis brevipedunculata	Amur peppervine	Vine
Amphicarpaea bracteata	American hog-peanut	Vine
Calystegia sepium	Western hedge bindweed	Vine
Campsis radicans	Trumpet creeper	Vine
Celastrus orbiculatus	Asian bittersweet	Vine
Clematis terniflora	Sweet autumn virginsbower	Vine
Convolvulus	Bindweed	Vine
Echinocystis lobata	Wild cucumber	Vine
Euonymus fortunei	Winter creeper	Vine
Hedera helix	English ivy	Vine
Ipomoea purpurea	Common morning glory	Vine
Lonicera japonica	Japanese honeysuckle	Vine
Mitchella repens	Partridge-berry	Vine
Parthenocissus quinquefolia	Virginia creeper	Vine
Persicaria perfoliata	Mile-a-minute	Vine
Polygonum perfoliatum	Asiatic tearthumb	Vine
Pueraria	Kudzu	Vine
Sicyos angulatus	One-seed burr-cucumber	Vine
Smilax	Greenbrier	Vine
Smilax bona-nox	Fringed greenbrier	Vine
Smilax glauca	Sawbrier	Vine
Smilax rotundifolia	Horsebrier	Vine
Toxicodendron radicans	Eastern poison ivy	Vine
Vinca major	Greater periwinkle	Vine
Vinca minor	Common periwinkle	Vine
Vitis	Grape	Vine
Vitis aestivalis	Summer grape	Vine
Vitis riparia	River-bank grape	Vine
Vitis rotundifolia	Muscadine	Vine
Wisteria floribunda	Japanese wisteria	Vine

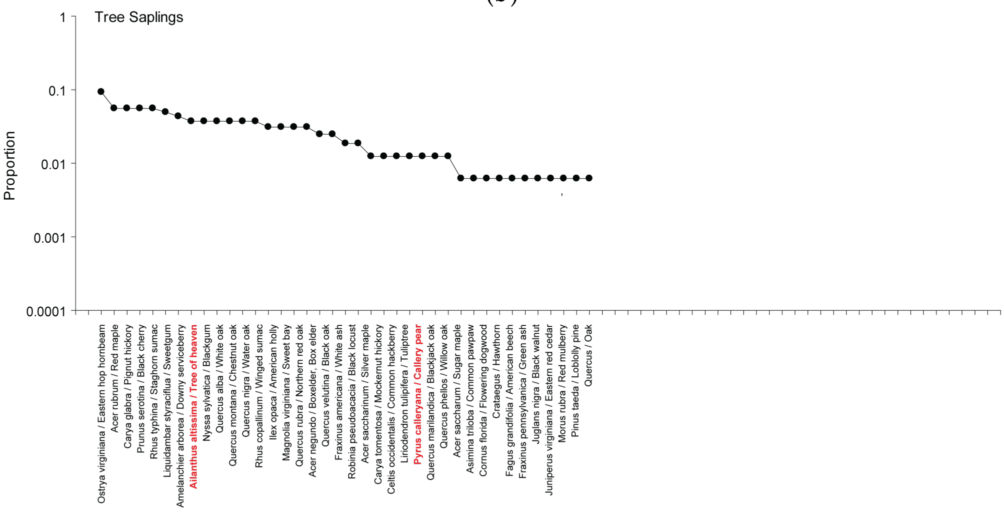


(a)

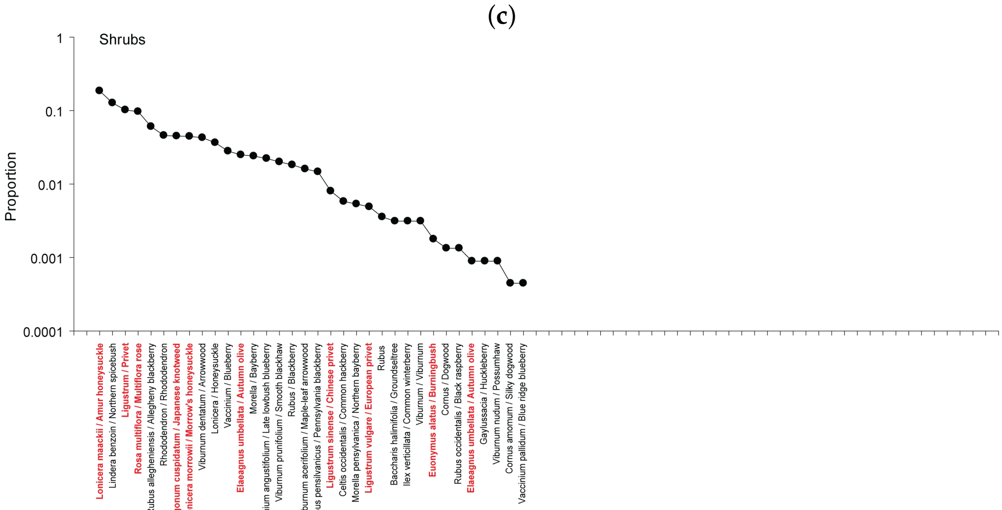
Figure A1. *Cont.*



(**b**)



(**c**)



(**d**)

Figure A1. Rank abundance of woody species by growth form. Rank abundance of (**a**) canopy trees, (**b**) tree saplings (**c**) tree seedlings, and (**d**) shrubs found across 100 urban-adjacent riparian forest patches in the coastal Chesapeake and Delaware Bay watersheds. Non-native species listed as invasive in one or more states within the study area are indicated in red.

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