Using i-Tree Canopy to Assess Tree Canopy Cover and Ecosystem Services of Three Urban Forests Within the George Washington Memorial Parkway

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A Case Study Report Prepared for

U.S. Department of the Interior
National Park Service
Urban Ecology Research Learning Alliance

August 5, 2023

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How to Cite This Report:

Wiseman, E., Chambard, A., Kelsch, P., and Heavers, N. (2023). *Using i-Tree Canopy to Assess Tree Canopy Cover and Ecosystem Services of Three Urban Forests Within the George Washington Memorial Parkway* (pp. 1–55). Virginia Tech, Blacksburg, Virginia. Available at URL.

Introduction

Urban forests are ecosystems found in areas of dense human settlement that possess key structural and functional traits inherent to all forests due to the predominance of trees as mediators of biogeochemical and ecological processes (Escobedo et al. 2019). When contextualized to human wellbeing and livelihood, these processes are referred to as ecosystem services. Broadly, these services are categorized as supporting, regulating, provisioning, and cultural services (Evans, 2022). While all services are important to people and the planet, much attention is paid to regulating ecosystem services because they mitigate many of the detrimental effects of urbanization and human activity on the environment (Marando et al. 2019). Key among these regulating services are carbon offsets, air pollution filtration, and stormwater capture (Livesley 2016).

Physical and physiological processes of trees interacting with their growing environment result in measurable changes in ecosystem conditions that can be quantified and correlated with environmental quality and human wellbeing. Important physiological processes of trees that influence regulating services include photosynthesis, respiration, gas exchange, and evapotranspiration (Roeland et al. 2019). These processes, in turn, are correlated to the leaf area within tree canopies. This leaf area is often assessed across large urban forests as the two-dimensional tree canopy cover observed remotely from above, either in terms of canopy acreage or percentage of the land area overshadowed by tree canopy. By assessing tree canopy cover, estimates can be derived for the ecosystem services of the urban forest (Nowak 2018). This information is useful for numerous purposes: advancing scientific knowledge, raising awareness of urban forest benefits, and directing conservation policies and management practices.

In this case study, we performed an assessment of tree canopy cover and associated ecosystem services for three urban forests within the George Washington Memorial Parkway (GWMP):

- Theodore Roosevelt Island, a designed and planted urban wilderness on a natural island
- Columbia Island, a conventional park of planted trees and lawn on a manmade island
- Arlington House Woodland, a mature temperate deciduous forest fragment

The GWMP is a 25-mile-long parkway that runs along the Potomac River in Virginia and Washington, DC from Mount Vernon to McLean. The three urban forests in this study lie in a roughly one-square mile area near the Arlington Memorial Bridge (Figure 1). Each of these urban forests has distinct cultural and ecological characteristics that differentiate one from the other. The historical land use, natural and unnatural disturbances, and management interventions have imparted unique characteristics that influence the structure and function of each urban forest. As a result, these sites offer an interesting opportunity first to examine the extent of tree canopy cover across diverse natural and built conditions and second to understand the contributions that tree canopy cover makes to ecosystem services in these local environments. Collectively, these three sites well represent a range of landscape conditions found throughout the GWMP. Therefore, this case study provides insight into urban forest structure and function across the entire GWMP.

For this assessment, we employed an urban forest analytical tool called i-Tree Canopy, which is a web-based software application developed by the U.S. Forest Service and its partners for free use by the public (Nowak 2021). The software allows users to assess and quantify tree canopy cover across a study area using visual interpretation of Google Earth imagery. Those data are then used to run models that estimate ecosystem services of tree canopy within the study area. Model outputs are provided in

tabular and graphical format. Outputs include a breakdown of tree canopy cover relative to other land cover types and estimates of carbon offsets, air pollution filtration, and stormwater capture from tree canopy.

This case study report is organized into four major sections:

In Section I, we begin with a description of the three study sites and how they were selected for the study. Details are shared about the location, size, and character of each site as it relates to the tree canopy and land cover observed there today. Aerial photos map are supplemented with ground-level photos to provide greater context for the character of each urban forest.

In Section II, we combine reporting of the case study methods and the findings of the assessment. The methods are broken into five steps so that the process of this assessment can be clearly comprehended and reproduced for similar urban forest assessments elsewhere. By combining the methods and findings, the reader can see how estimates of tree canopy and ecosystem services are derived through each step of the assessment.

In Section III, we discuss the findings of the assessment and compare and contrast the data generated for each of the urban forests. We also compare the results of this assessment to similar data extracted from another recent tree canopy and land cover analysis by the Chesapeake Conservancy using an alternative remote sensing technology. Important limitations of our study methods and reliability of the model outputs are also discussed.

In Section IV, we conclude with a future perspective on how this assessment is useful for understanding the larger context of the GWMP urban forest and how others with similar interest in tree canopy and ecosystem services might adopt this assessment method.

In the back matter of the report, we have compiled an extensive set of 13 appendices showing the detailed outputs of the i-Tree Canopy analysis of tree canopy cover and ecosystem services. Also included are land cover maps created for the three study sites from the 2017-2018 Chesapeake Conservancy land cover analysis.

Section I. Study Sites Selection and Description

Each of the three study sites has a distinct and significant history within the broader natural and cultural landscapes of the GWMP, which has in turn influenced the current forest cover types. Theodore Roosevelt Island has a long history dating to Native American inhabitation, a colonial-era private estate, use as a military training grounds, and is currently a presidential memorial to Theodore Roosevelt. As part of the development of the memorial, the forest was intentionally restored and designed to become a wilderness island in commemoration of the importance of the exploration of nature to Theodore Roosevelt. Columbia Island, now Lady Bird Johnson Park, was the centerpiece of the First Lady's Capital Beautification program. The island was planted extensively with specimen shade trees and flowering trees in the late 1960s, and many of these have matured into large open-grown landscape trees with mowed turf as the ground cover. The Lyndon Baines Johnson Memorial Grove was added to the park in the 1970s. It is a planted stand of white pines surrounding a granite megalith with an adjoining picnic meadow of pines, deciduous trees, and ornamental plantings. In some places, the trees have formed a closed canopy, often with duff and pine needles covering the ground. The Arlington House Woodland is a remnant stand of older trees in an isolated ravine in Arlington Cemetery, preserved by George Washington's adopted grandson over 200 years ago. These landscape histories have influenced which forest types grow on these sites and therefore the ecological services they provide.

Figure 1. Location of study sites: (1) Theodore Roosevelt Island, (2) Columbia Island, (3) Arlington House Woodland.

Theodore Roosevelt Island

Theodore Roosevelt Island is a 90-acre natural island in the Potomac River between Georgetown (Washington, DC) and Arlington, VA. It was a fishing and agriculture hub of the native peoples known as the Anacostans before the early 18th century when the Mason family took possession of the land. Theodore Roosevelt Island has had several diverse periods of use since the Mason ownership, including occupation during the Civil War, an amusement park, and now the Presidential Memorial. The Olmsted Brothers landscape architecture firm designed and planted the island as a memorial forest in the 1930s to honor Roosevelt's legacy of conserving significant American landscapes. Past uses were erased and native trees were planted to make the island look like wilderness. In the 1960s a memorial plaza was constructed in the forest (Figure 2). The plaza is now considered the Presidential Memorial with the evolving forest as a backdrop.

Figure 2. A view of the monument and memorial plaza, encircled by a grove of planted willow oaks, on Theodore Roosevelt Island.

Columbia Island

Columbia Island is a 130-acre manmade island that was created from sediment dredged from the Potomac River, and presumably, has undifferentiated soils built up in several layers of fill. The oldest trees on the island are a handful of cottonwoods, willows, and silver maples on the southern finger of the island, where there was less disturbance from the construction of the roadways that traverse the island. Most of the island was planted in the late 1960s with many deciduous trees, especially oaks and maples, and large areas of mowed grass between and under these open-grown trees (Figure 3). This was the centerpiece of Lady Bird Johnson's capital beautification project, and the island is now named Lady Bird Johnson Park in her honor. Flowering dogwoods were planted extensively, and though many died, with repeated plantings they are becoming prominent across the island. The Lyndon Baines Johnson Memorial Grove is a substantial grove of white pines planted in the 1970s with additional ornamental trees and shrubs adding diversity of vegetation to the grove.

Figure 3. A view of the parklike setting on Columbia Island with extensive lawn and scattered landscape trees in the foreground and the George Washington Memorial Parkway in the background.

Arlington House Woodland

Arlington House Woodland is a 12-acre native forest fragment surrounded by Arlington National Cemetery. The timber has remained uncut since at least 1802, when George Washington Park Custis, George Washington's adopted grandson, inherited the woods at the heart of 1,100 acres.

Figure 4. A view of the northern edge of the Arlington House Woodland flanked on the left by an access road and graves of Arlington National Cemetery.

Custis valued the forest on the north side of his neoclassical mansion—Arlington House—and preserved it as part of his extensive landscape garden sweeping down from the hilltop estate. Custis was able to preserve the woods in part because he also inherited an extensive forest tract near Four Mile Run several miles west of Arlington House and had no shortage of timber to harvest there. The Arlington House Woodland grows on the slopes of a ravine, a gravel terrace with a perennial spring running from the foot of the slope and through the forest (Figure 4). The canopy trees consist of oak, hickory, tulip tree, and beech, and some are approximately 250 years old.

Section II. Case Study Methods and Findings

For this report, we have opted to present here the methods and findings simultaneously in order to easily show the linkage between our approach to studying these urban forests and what we discovered about land cover composition and tree canopy ecosystem services Our use of i-Tree Canopy for this study followed a five-step process that started with delineating the geographic boundary of each study area and concluded with data interpretation. In the pages below, we describe the methods and findings of each step in the assessment process.

Step 1. Delineate the boundary and landscape typology for each site

Step 2. Define the tree canopy and land cover classification scheme

Step 3. Perform visual interpretation of sample points overlaid on aerial images

Step 4. Generate statistics for tree canopy and land cover

Step 5. Estimate ecosystem services of tree canopy

Step 1. Delineate Site Boundaries and Landscape Typologies

To delineate the assessment boundary for each site, we first subdivided them into landscape types based on ecological characteristics of each urban forest. The criteria used to define these landscapes included biophysical and cultural influences on the character and composition of each forest. These subdivisions allowed for a more detailed analysis of tree canopy within site. We started this subdivision process by examining each urban forest using Google Earth imagery, which is an effective way to understand landscape variability and typology across large areas. We then corroborated our aerial observations with field observations made in July 2022 to better understand how the character of the forest in three-dimensional space compared to the aerial imagery. This was a real benefit to determining the edges between the landscape subdivisions we defined. The images on the following pages (Figures 5 through 10) show how the forest at each site was subdivided into landscape types. The sequence of images follows a progression of a site overview image taken from Google Earth (from May 2022) showing the urban forest boundary, followed by an overlay of landscape type delineations, and then supporting ground-level photos that show the typical character of the vegetation in each landscape type. The sequence follows Theodore Roosevelt Island, Columbia Island, and the Arlington House Woodland.

Theodore Roosevelt Island

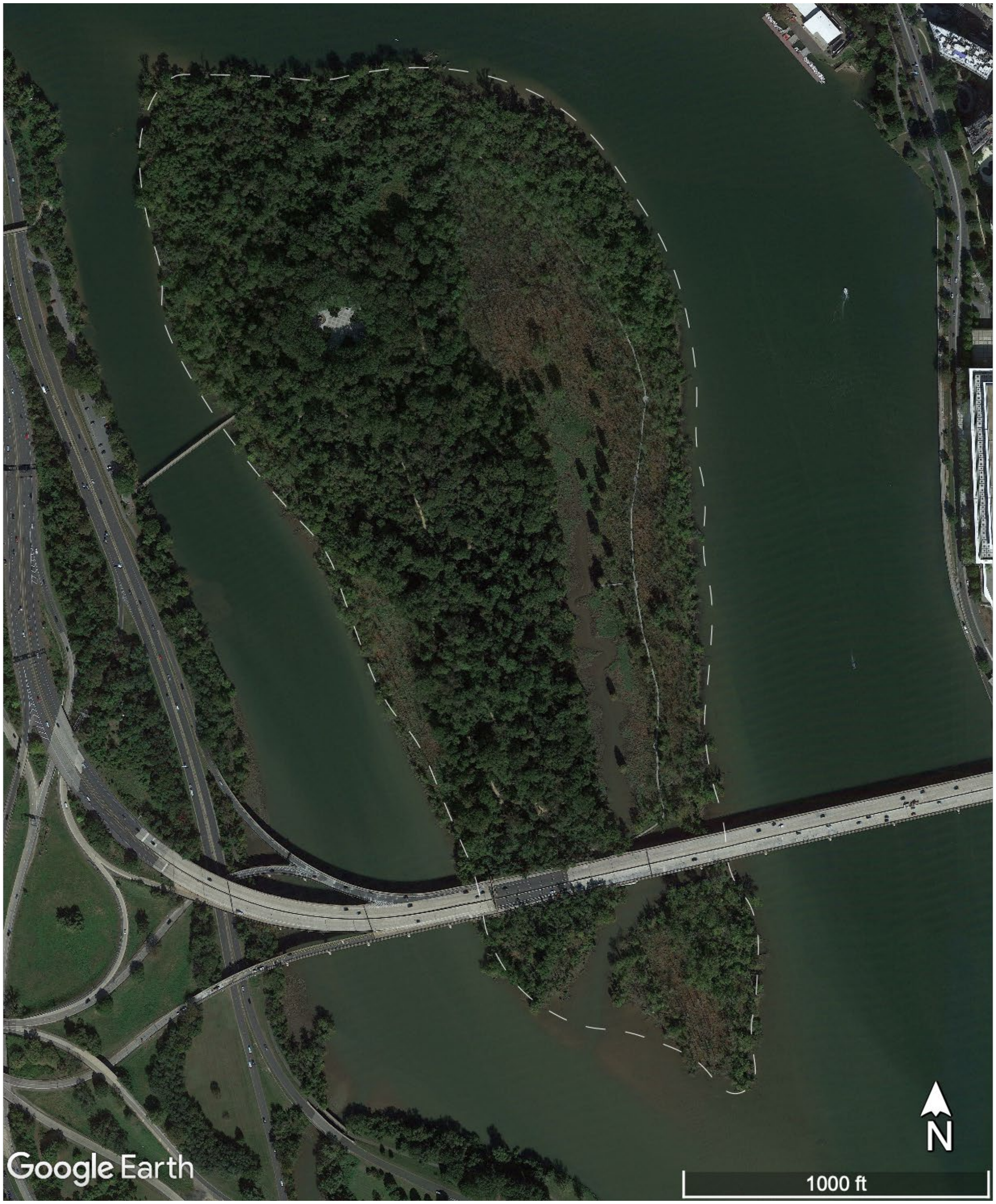

Figure 5. Satellite image of Theodore Roosevelt Island captured in May 2022 acquired from Google Earth with boundary delimited by white dash line.

Theodore Roosevelt Island

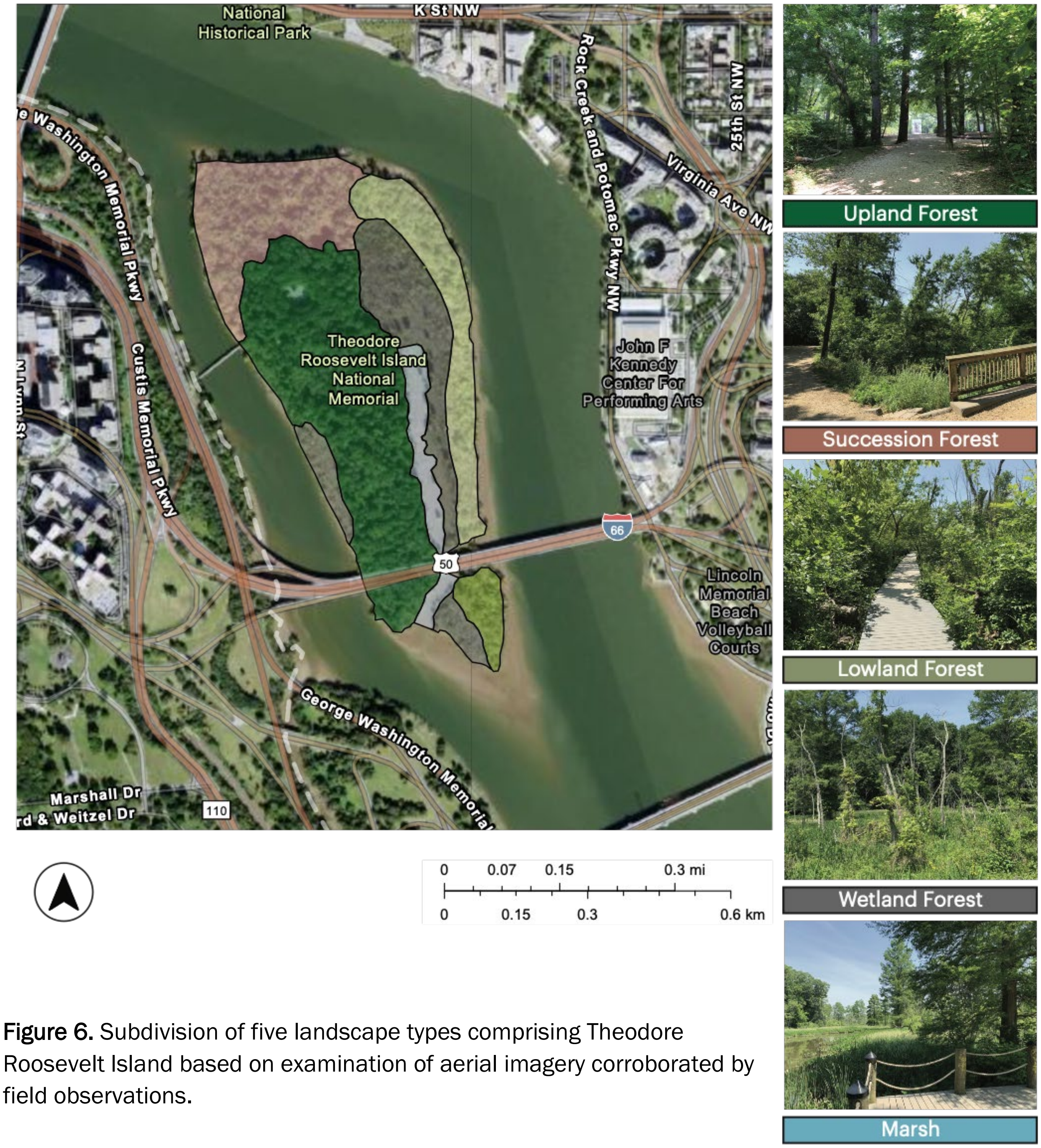

Figure 6. Subdivision of five landscape types comprising Theodore Roosevelt Island based on examination of aerial imagery corroborated by field observations.

Theodore Roosevelt Island was subdivided into five landscape types based on characteristics of the vegetation and terrain that were discernible in aerial imagery and validated by ground inspection.

Upland Forest is high elevation and contains tall trees generating a typical forest. Succession Forest is confined to the northwest corner where disturbance has fragmented the forest an spurred pioneer and invasive plant establishment. Lowland Forest is along the east side abutting the shoreline. Wetland Forest occupies the center of the island where trees are sparser. Marsh surrounds a drainage channel at the island center and is predominantly low vegetation of shrubs and herbaceous plants.

Columbia Island

Figure 7. Satellite image of Columbia Island captured in May 2022 acquired from Google Earth with boundary delimited by white dash line.

Columbia Island

Figure 8. Subdivision of three landscape types comprising Columbia Island based on examination of aerial imagery corroborated by field observations.

Columbia Island was subdivided into three landscape types, where cultural and ecosystem characteristics are linked. The Woodland landscape is in the center of the island where some trees are native, but most of them are planted to create the Lyndon Baines Johnson Memorial. On the west edge of the island is a narrow band of Succession Forest, where native trees and shrubs are naturally regenerating along the banks of the channel. The largest area is Parkland, where lawns and landscape trees are intermixed.

Arlington House Woodland

Figure 9. Satellite image of the Arlington House Woodland captured in May 2022 acquired from Google Earth with boundary delimited by white dash line.

Arlington House Woodland

Figure 10. Subdivision of two landscape types comprising the Arlington House Woodland based on examination of aerial imagery corroborated by field observations.

The Arlington House Woodland was subdivided into two landscape types. The Upland Forest is the most prevalent type, which is found at the highest elevation close to Arlington House. It is the portion of the woodland with the greatest structural and compositional integrity, comprising mostly temperate hardwood tree species in the overstory and mixed species in the midstory and understory. The northern portion of the woodland has been repeatedly disturbed and encroached upon over the decades, creating edge effects on vegetation composition. We identified this portion as Succession Forest where herbaceous plants and shrubs are intermixed in canopy gaps and along the forest edge.

Step 2. Define the Tree Canopy and Land Cover Classification Scheme

Having identified and mapped distinct landscape zones across each site, the next step was to create tree canopy and land cover classification scheme to be used in the visual interpretation of the aerial imagery. In creating this scheme, we were particularly interested in differentiating tree cover from other types of vegetation. Furthermore, we sought to differentiate forest tree canopy from landscape tree canopy because they have distinct ecological and cultural characterizes relevant to their conservation and management. Finally, we had to ensure that the classification scheme was comprehensive, meaning that every spot on the landscape could be exclusively and unambiguously assigned to one of the cover classes we defined, while not differentiating too many categories. This makes the visual interpretation process easier and also provides a more detailed analysis.

Based on the considerations above, we settled on a classification scheme comprising nine cover classes:

- Forest tree canopy
- Landscape tree canopy
- Low vegetation
- Shadow or gap
- Lawn
- Duff or mulch
- Soil or bare ground
- Water
- Impervious

The following sequence of aerial images shows landscape scenes typifying each of the nine cover classes. Shown near the center of each image is a yellow cross-hair, which is the exact location of the sampling point for visual interpretation of the cover class in that scene. Red lines superimposed on the images are boundaries of landscape types. The colored squares designate the cover classes in subsequent charts shown in the report.

Forest Tree Canopy: This cover class includes trees in stand-like conditions where trees are densely spaced and it is difficult to differentiate individual trees.

Landscape Tree Canopy: This cover class includes trees in park-like conditions where trees are loosely spaced and it is easy to differentiate individual trees.

Low Vegetation: This cover class includes non-tree vegetation such as shrubs, vines, and herbaceous plants lacking tree canopy directly above and not maintained through periodic mowing.

Shadow or Gap: This cover class includes locations where the cover class cannot be determined because there is dark shade (often in a canopy gap) that obscures classification.

Lawn: This cover class includes grass that is mowed periodically and does not have tree canopy or taller vegetation directly above it.

Duff or Mulch: This cover class includes dead vegetative debris occurring either as a natural groundcover or applied as mulch in a managed landscape.

Soil or Bare Ground: This cover class includes ground covered by gravel, natural rock, or exposed soil.

Water: This cover class includes natural and man-made features that routinely hold standing water and do not have tree canopy or taller vegetation directly above it.

Impervious: This cover class includes buildings, paved roads, etc. that seal the soil surface and do not have tree canopy or taller vegetation directly above it.

Step 3. Perform Visual Interpretation of Sample Points

Within i-Tree Canopy, assessment of tree canopy and land cover for a study site entails sample point visual interpretation of aerial imagery (Parmehr et al. 2016). The program generates a random sample of interpretation points overlaid on a Google Earth aerial image. The sample size (number of visual interpretation points) prescribed to assess a study site is dictated by the acreage of the site and the variability in tree canopy and land cover across the site. The larger and more variable the study site, the greater the sample size that is prescribed. Through testing of varying point sample sizes, we determined that visually interpreting about 20 sample points per acre in each study area provided us with a desired level of accuracy in classification estimates and tolerable sampling error (amount of statistical uncertainty).

After determining the appropriate point sample size for each site, we proceeded with performing visual interpretation of tree canopy and land cover using i-Tree Canopy (Figure 11). We created GIS shapefiles (boundary lines) for the landscape typology created in Step 1 of the process described above. Therefore, each site comprised two to five subdivisions that were separately assessed in i-Tree Canopy. This allowed us to examine patterns of tree canopy and land cover by landscape type within each of the three sites. In total, we performed ten i-Tree Canopy assessments across the three sites.

- Theodore Roosevelt Island (5 landscape types):
  Upland Forest, Succession Forest, Lowland Forest, Wetland Forest, Marsh
- Columbia Island (3 landscape types):
  Woodland, Succession Forest, Parkland
- The Arlington House Woodland (2 landscape types):
  Upland Forest, Succession Forest

The i-Tree program provides a user interface that displays Google Earth imagery overlaid by the randomized sample points. The analyst then pans and zooms the map interface to each sample point and classifies the cover class based on visual cues in the image consistent with the definitions of the nine cover classes. The software keeps a running tally of the sample point classifications until the desired sample size is completed. The raw data for the latitude/longitude and cover classification of each sample point is saved in a project file that can be reviewed and edited at a later time as needed.

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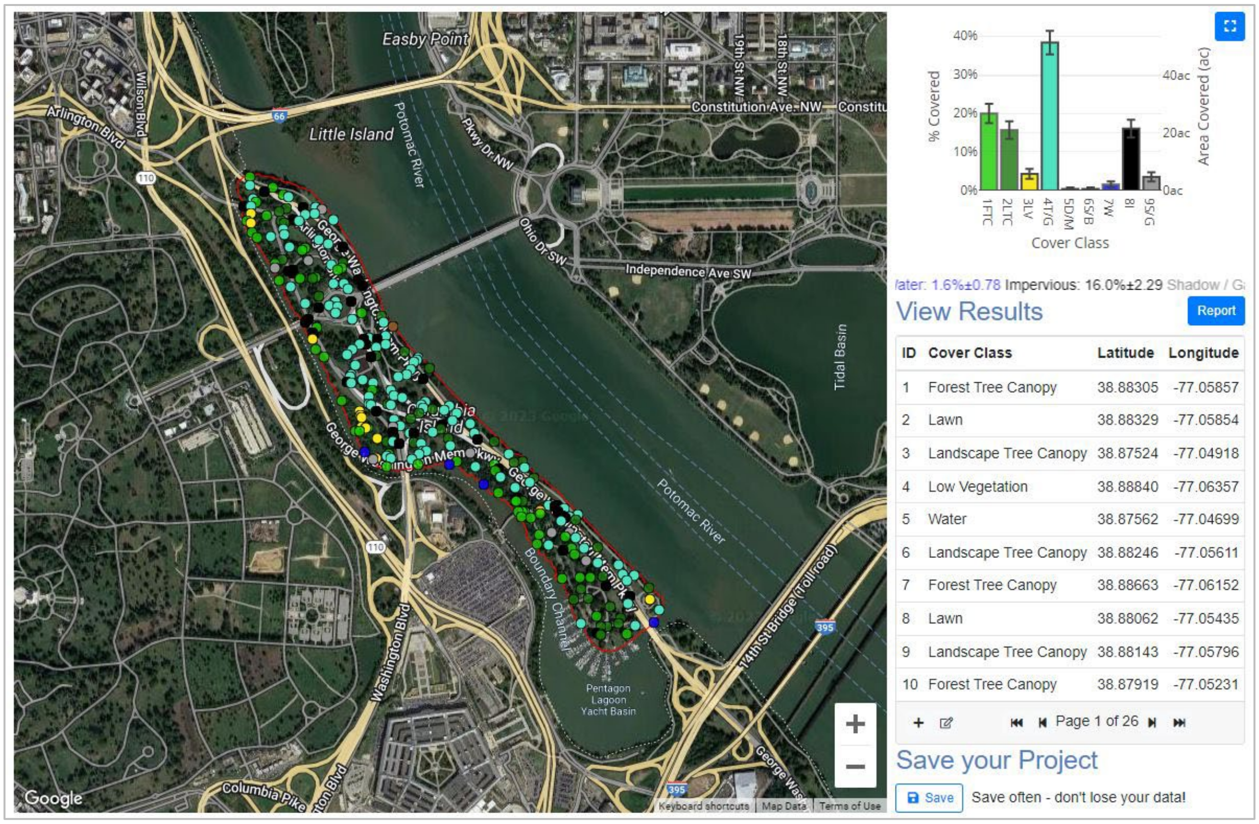

Figure 11. Screen capture of the i-Tree Canopy user interface showing sample points randomized across Columbia island in the process of visual interpretation to classify the tree canopy and land cover.

Step 4. Generate Statistics for Tree Canopy and Land Cover

The following charts (Figures 12 through 21) and tables (Tables 1 through 10) display the results of the i-Tree Canopy assessment for each landscape type within each site. The bar chart shows the distribution of tree canopy and land cover classes both in terms of acreage and land area percentage within each landscape subdivision of a site. The table shows the breakdown of sample point interpretation of aerial imagery based on the classification scheme. The estimates of acreage and land area percentage are presented along with the standard error (SE) of each estimate. Highlighted by the green box in each table are the two cover classes comprising tree canopy, which are combined in the subsequent modeling of regulating ecosystem services. The black box highlights the total point sample size for the site–landscape type combination. In Table 11 is shown a summary of tree canopy cover data broken down by the three sites and their respective landscape types.

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Theodore Roosevelt Island – Upland Forest

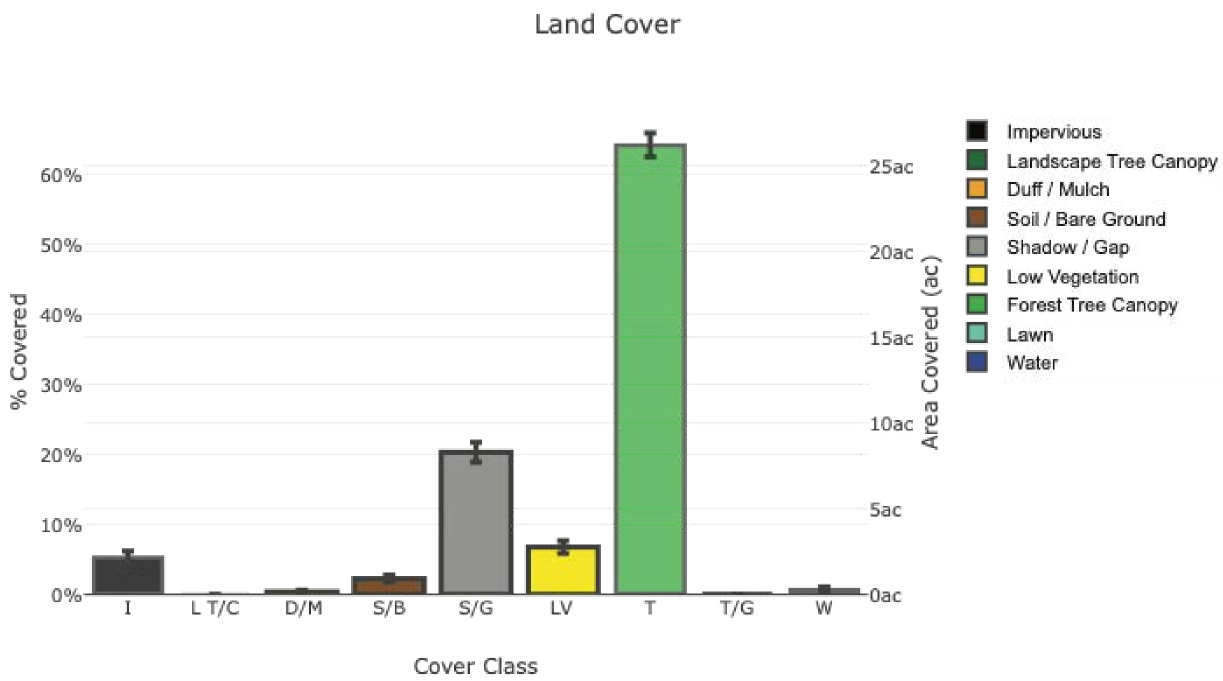

Figure 12. Tree canopy and land cover assessment of the Upland Forest within Theodore Roosevelt Island.

Table 1. Tree canopy and land cover assessment of the Upland Forest within Theodore Roosevelt Island.

Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
I	Impervious		43	5.39 ± 0.80	2.20 ± 0.33
L T/C	Landscape Tree Canopy		0	0.00 ± 0.00	0.00 ± 0.00
D/M	Duff / Mulch		3	0.38 ± 0.22	0.15 ± 0.09
S/B	Soil / Bare Ground		18	2.26 ± 0.53	0.92 ± 0.21
S/G	Shadow / Gap		162	20.30 ± 1.42	8.29 ± 0.58
LV	Low Vegetation		54	6.77 ± 0.89	2.76 ± 0.36
TC	Forest Tree Canopy		512	64.16 ± 1.70	26.21 ± 0.69
La	Lawn		0	0.00 ± 0.00	0.00 ± 0.00
W	Water		6	0.75 ± 0.31	0.31 ± 0.13
Total			**798**	**100.00**	**40.86**

Theodore Roosevelt Island – Succession Forest

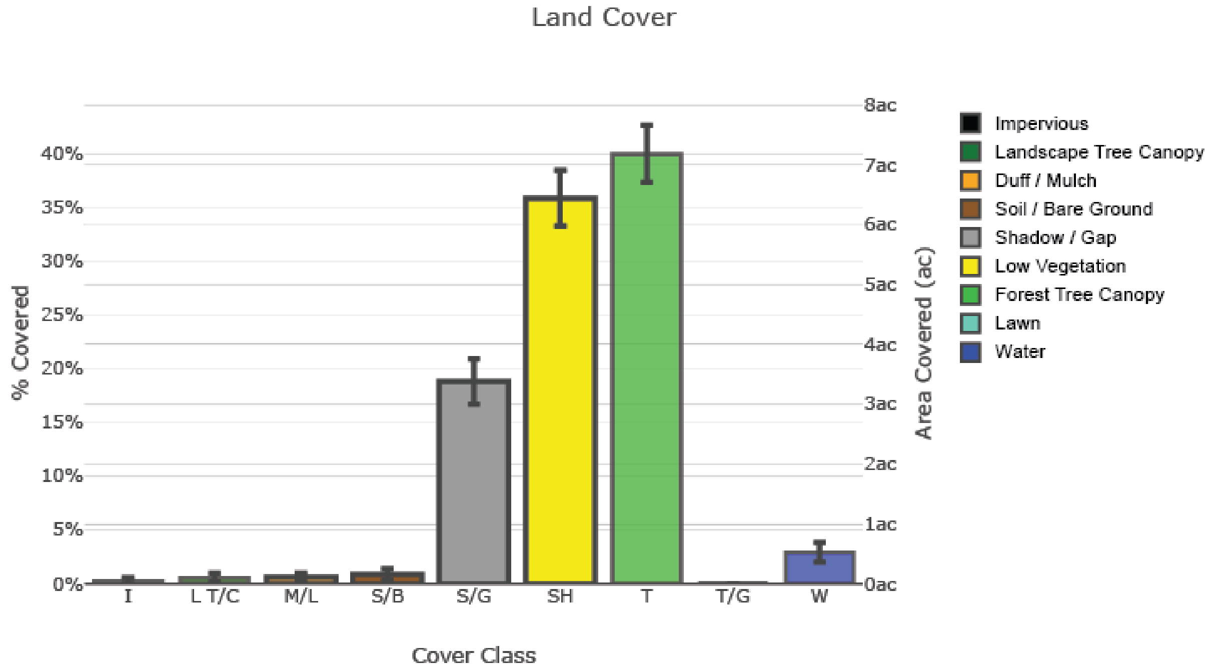

Figure 13. Tree canopy and land cover assessment of the Succession Forest within Theodore Roosevelt Island.

Table 2. Tree canopy and land cover assessment of the Succession Forest within Theodore Roosevelt Island.

Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
I	Impervious		1	0.29 ± 0.29	0.05 ± 0.05
L T/C	Landscape Tree Canopy		2	0.59 ± 0.42	0.11 ± 0.07
D/M	Duff / Mulch		2	0.59 ± 0.42	0.11 ± 0.07
S/B	Soil / Bare Ground		3	0.88 ± 0.51	0.16 ± 0.09
S/G	Shadow / Gap		64	18.82 ± 2.12	3.38 ± 0.38
Lv	Low Vegetation		122	35.88 ± 2.60	6.44 ± 0.47
T	Forest Canopy		136	40.00 ± 2.66	7.18 ± 0.48
La	Lawn		0	0.00 ± 0.00	0.00 ± 0.00
W	Water		10	2.94 ± 0.92	0.53 ± 0.16
Total			**340**	**100.00**	**17.96**

Theodore Roosevelt Island – Lowland Forest

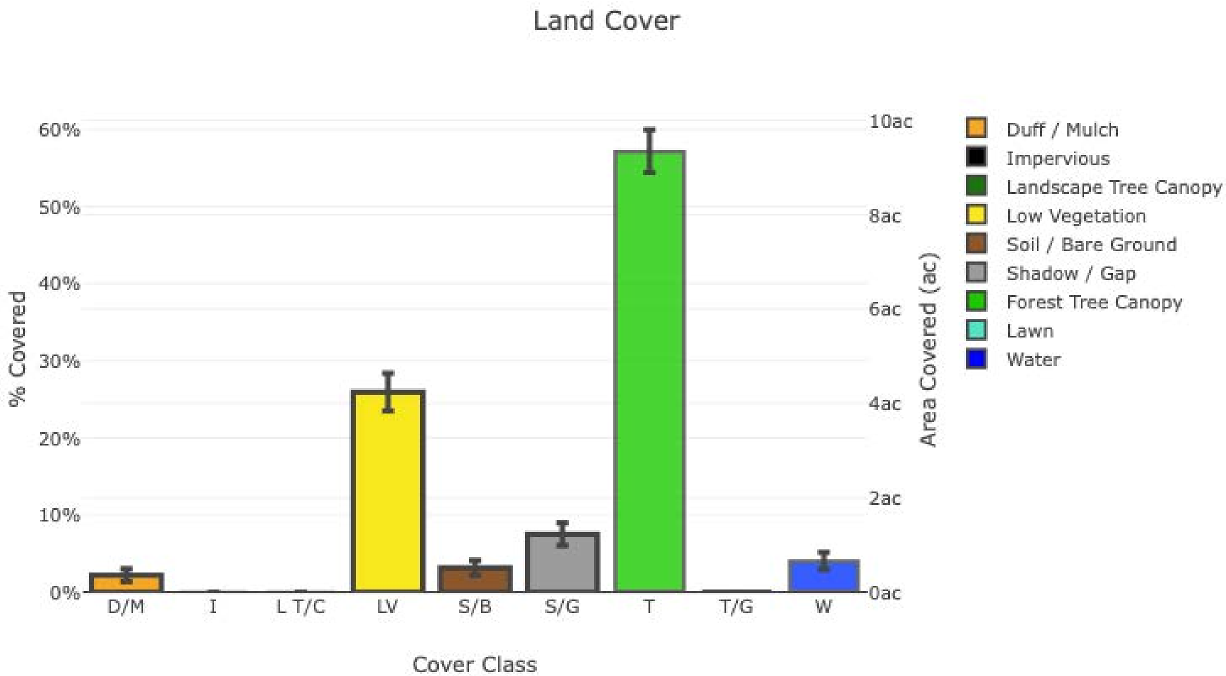

Figure 14. Tree canopy and land cover assessment of the Lowland Forest within Theodore Roosevelt Island.

Table 3. Tree canopy and land cover assessment of the Lowland Forest within Theodore Roosevelt Island.

Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
D/M	Duff / Mulch		7	2.19 ± 0.83	0.36 ± 0.14
I	Impervious		0	0.00 ± 0.00	0.00 ± 0.00
L T/C	Landscape Tree Canopy		0	0.00 ± 0.00	0.00 ± 0.00
LV	Low Vegetation		83	25.94 ± 2.45	4.24 ± 0.40
S/B	Soil / Bare Ground		10	3.13 ± 0.97	0.51 ± 0.16
S/G	Shadow / Gap		24	7.50 ± 1.47	1.23 ± 0.24
T	Forest Tree Canopy		183	57.19 ± 2.77	9.35 ± 0.45
T/G	Lawn		0	0.00 ± 0.00	0.00 ± 0.00
W	Water		13	4.06 ± 1.10	0.66 ± 0.18
Total			**320**	**100.00**	**16.34**

<u>**Theodore Roosevelt Island – Wetland Forest**</u>

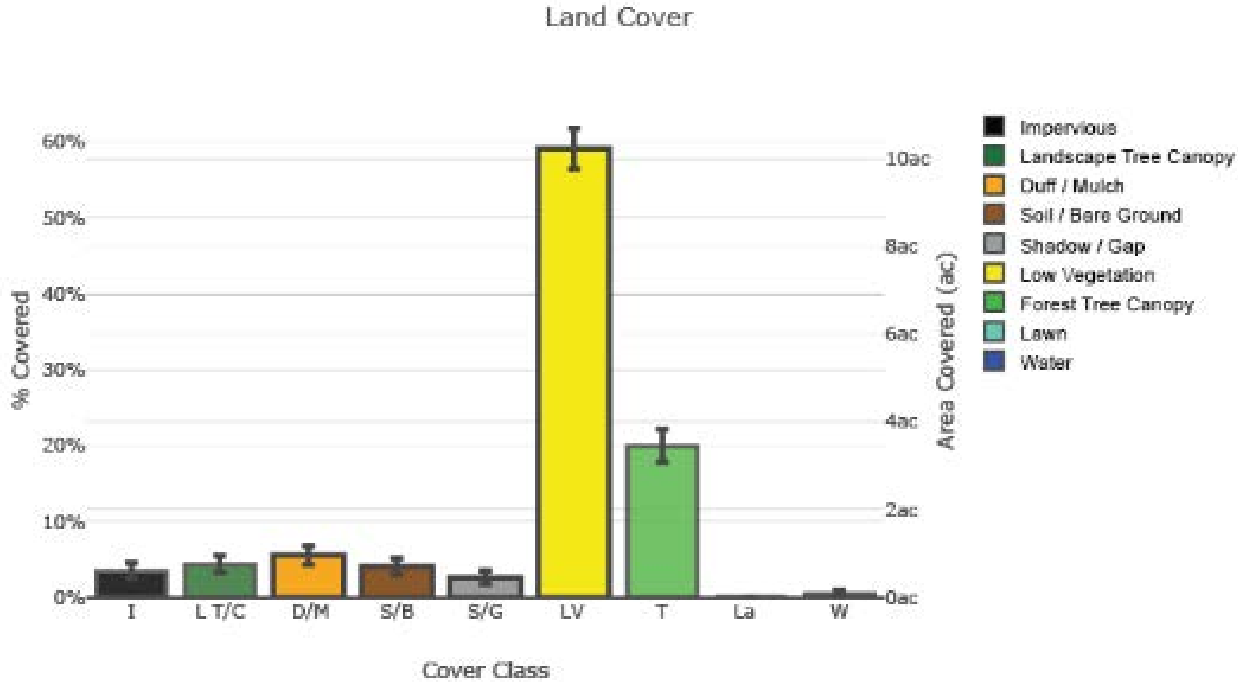

Figure 15. Tree canopy and land cover assessment of the Wetland Forest within Theodore Roosevelt Island.

Table 4. Tree canopy and land cover assessment of the Wetland Forest within Theodore Roosevelt Island.

Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
I	Impervious		12	3.53 ± 1.00	0.61 ± 0.17
L T/C	Landscape Tree Canopy		15	4.41 ± 1.11	0.76 ± 0.19
D/M	Duff / Mulch		19	5.59 ± 1.25	0.97 ± 0.22
S/B	Soil / Bare Ground		14	4.12 ± 1.08	0.71 ± 0.19
S/G	Shadow / Gap		9	2.65 ± 0.88	0.46 ± 0.15
LV	Low Vegetation		201	59.12 ± 2.67	10.23 ± 0.46
T	Forest Tree Canopy		68	20.00 ± 2.17	3.46 ± 0.38
La	Lawn		0	0.00 ± 0.00	0.00 ± 0.00
W	Water		2	0.59 ± 0.42	0.10 ± 0.07
Total			**340**	**100.00**	**17.30**

Theodore Roosevelt Island – Marsh

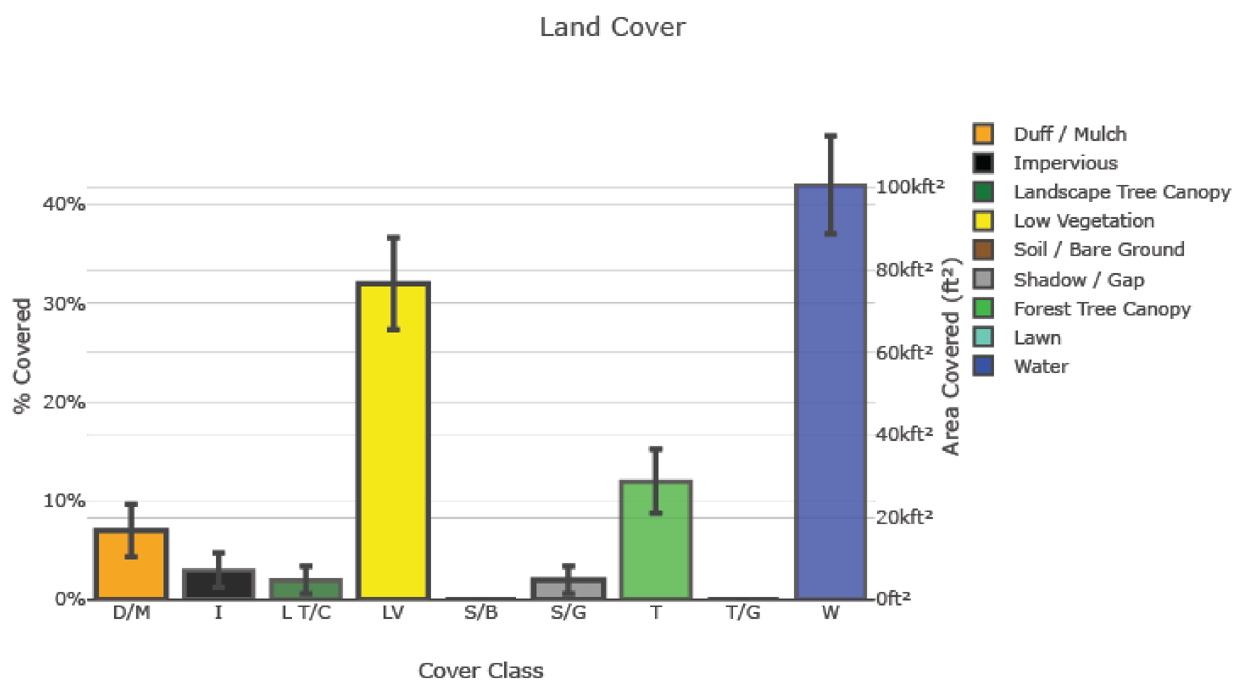

Figure 16. Tree canopy and land cover assessment of the Marsh within Theodore Roosevelt Island.

Table 5. Tree canopy and land cover assessment of the Marsh within Theodore Roosevelt Island.

Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ft²) ± SE
D/M	Duff / Mulch		7	7.00 ± 2.65	16782.75 ± 6343.28
I	Impervious		3	3.00 ± 1.73	7192.61 ± 4152.65
L T/C	Landscape Tree Canopy		2	2.00 ± 1.41	4795.07 ± 3390.63
LV	Low Vegetation		32	32.00 ± 4.66	76721.16 ± 11183.93
S/B	Soil / Bare Ground		0	0.00 ± 0.00	0.00 ± 0.00
S/G	Shadow / Gap		2	2.00 ± 1.41	4795.07 ± 3390.63
T	Forest Tree Canopy		12	12.00 ± 3.25	28770.43 ± 7791.07
T/G	Lawn		0	0.00 ± 0.00	0.00 ± 0.00
W	Water		42	42.00 ± 4.94	100696.52 ± 11833.24
Total			**100**	**100.00**	**239753.62**

Columbia Island – Woodland

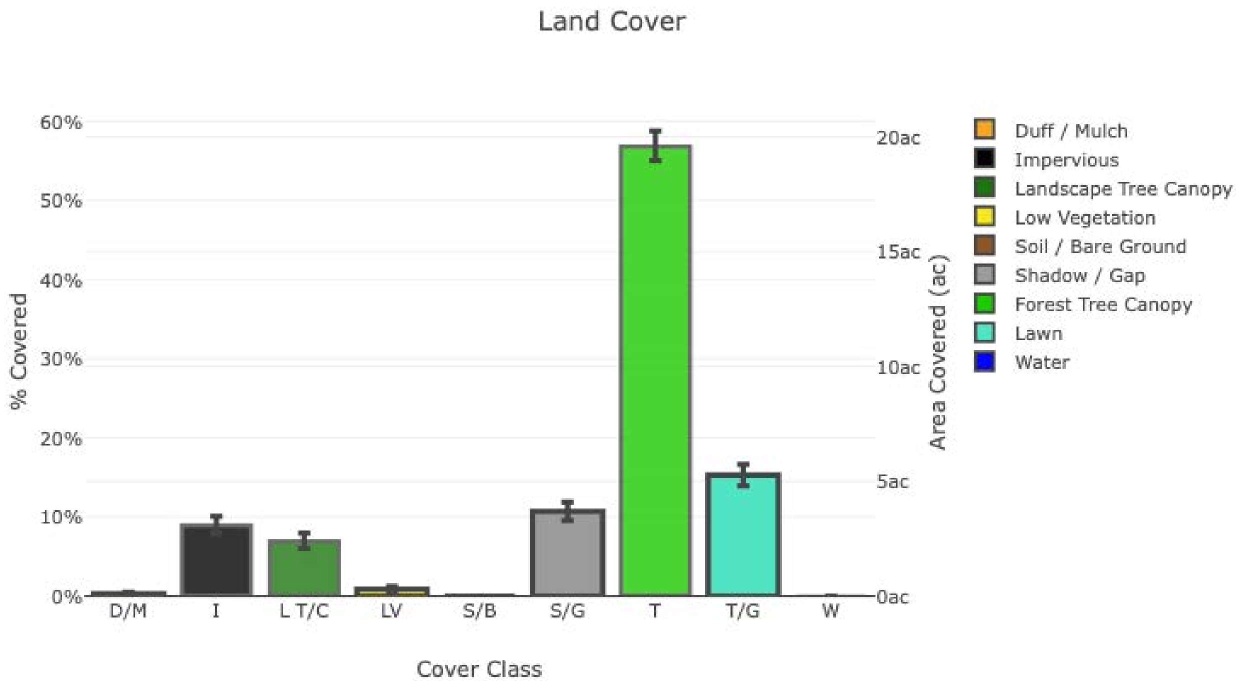

Figure 17. Tree canopy and land cover assessment of the Woodland within Columbia Island.

Table 6. Tree canopy and land cover assessment of the Woodland within Columbia Island.

Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
D/M	Duff / Mulch		2	0.29 ± 0.20	0.10 ± 0.07
I	Impervious		63	9.00 ± 1.08	3.10 ± 0.37
L T/C	Landscape Tree Canopy		49	7.00 ± 0.96	2.41 ± 0.33
LV	Low Vegetation		6	0.86 ± 0.35	0.30 ± 0.12
S/B	Soil / Bare Ground		0	0.00 ± 0.00	0.00 ± 0.00
S/G	Shadow / Gap		75	10.71 ± 1.17	3.69 ± 0.40
T	Forest Tree Canopy		398	56.86 ± 1.87	19.60 ± 0.65
T/G	Lawn		107	15.29 ± 1.36	5.27 ± 0.47
W	Water		0	0.00 ± 0.00	0.00 ± 0.00
Total			**700**	**100.00**	**34.47**

Columbia Island – Succession Forest

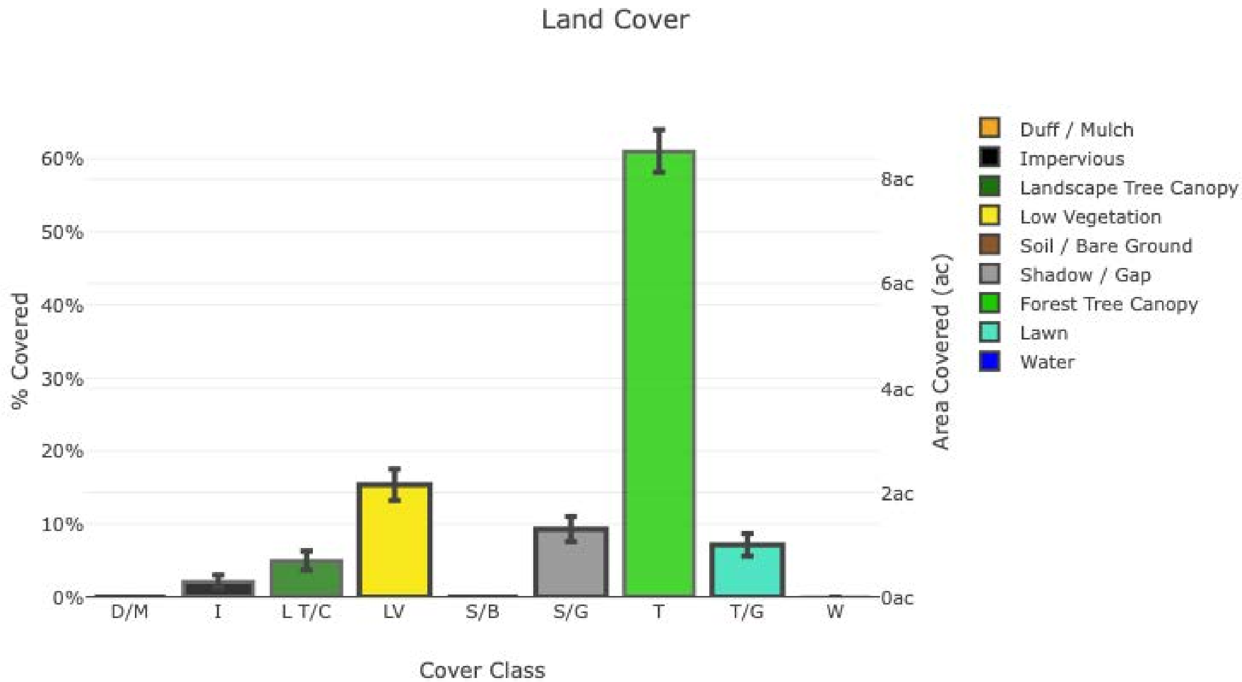

Figure 18. Tree canopy and land cover assessment of the Succession Forest within Columbia Island.

Table 7. Tree canopy and land cover assessment of the Succession Forest within Columbia Island.

Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
D/M	Duff / Mulch		0	0.00 ± 0.00	0.00 ± 0.00
I	Impervious		6	2.14 ± 0.87	0.30 ± 0.12
L T/C	Landscape Tree Canopy		14	5.00 ± 1.30	0.70 ± 0.18
LV	Low Vegetation		43	15.36 ± 2.15	2.15 ± 0.30
S/B	Soil / Bare Ground		0	0.00 ± 0.00	0.00 ± 0.00
S/G	Shadow / Gap		26	9.29 ± 1.73	1.30 ± 0.24
T	Forest Tree Canopy		171	61.07 ± 2.91	8.53 ± 0.41
T/G	Lawn		20	7.14 ± 1.54	1.00 ± 0.22
W	Water		0	0.00 ± 0.00	0.00 ± 0.00
Total			**280**	**100.00**	**13.97**

Columbia Island – Parkland

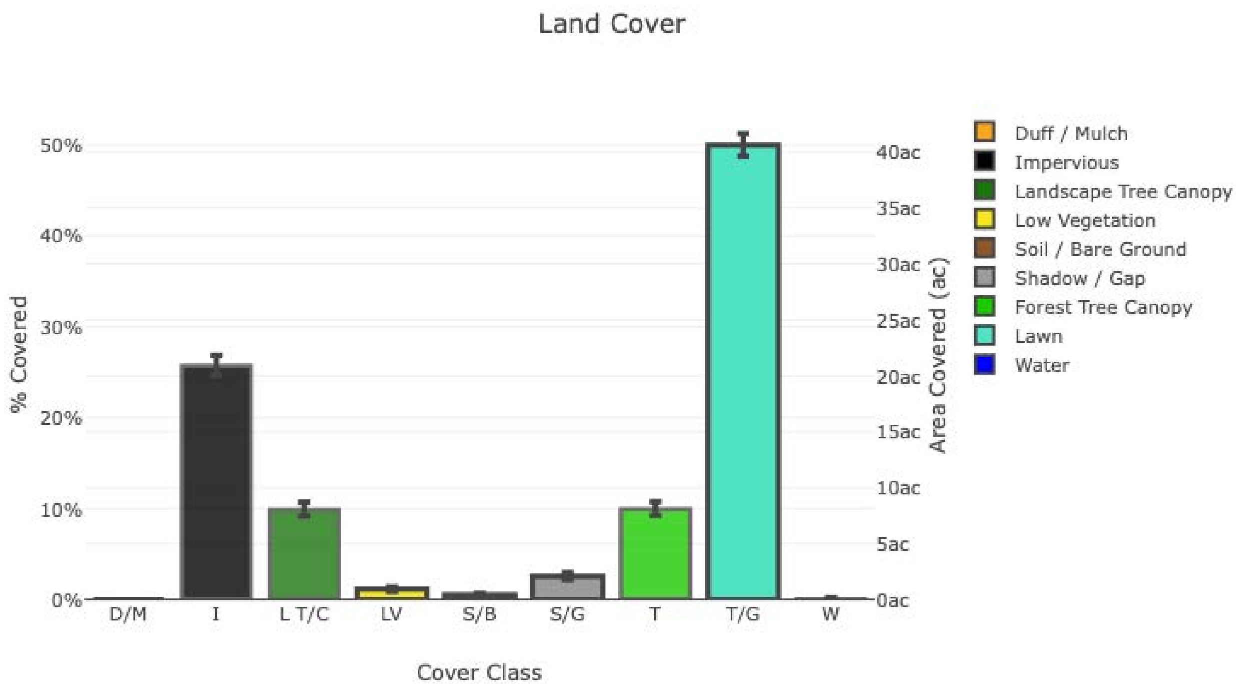

Figure 19. Tree canopy and land cover assessment of the Parkland within Columbia Island.

Table 8. Tree canopy and land cover assessment of the Parkland within Columbia Island.

Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
D/M	Duff / Mulch		0	0.00 ± 0.00	0.00 ± 0.00
I	Impervious		412	25.75 ± 1.09	20.92 ± 0.89
L T/C	Landscape Tree Canopy		159	9.94 ± 0.75	8.07 ± 0.61
LV	Low Vegetation		18	1.13 ± 0.26	0.91 ± 0.21
S/B	Soil / Bare Ground		8	0.50 ± 0.18	0.41 ± 0.14
S/G	Shadow / Gap		41	2.56 ± 0.40	2.08 ± 0.32
T	Forest Tree Canopy		160	10.00 ± 0.75	8.12 ± 0.61
T/G	Lawn		800	50.00 ± 1.25	40.62 ± 1.02
W	Water		2	0.13 ± 0.09	0.10 ± 0.07
Total			**1600**	**100.00**	**81.25**

Arlington House Woodland – Upland Forest

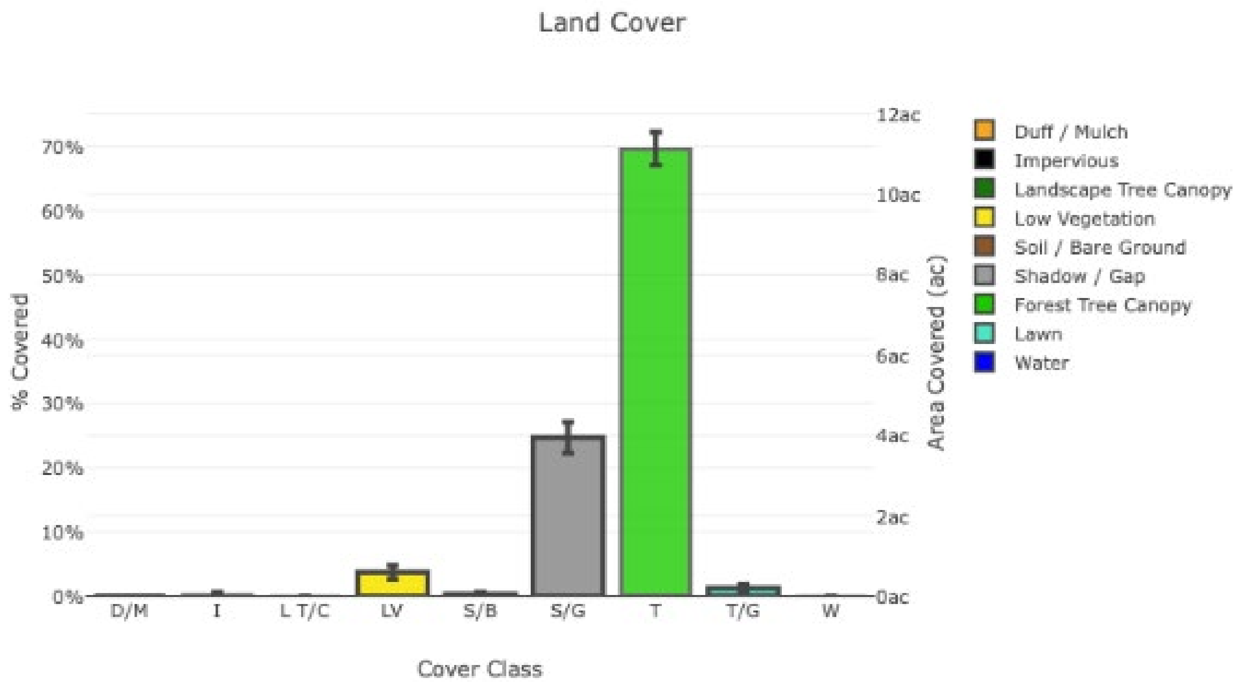

Figure 20. Tree canopy and land cover assessment of the Upland Forest within the Arlington House Woodland.

Table 9. Tree canopy and land cover assessment of the Upland Forest within the Arlington House Woodland.

Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
D/M	Duff / Mulch		0	0.00 ± 0.00	0.00 ± 0.00
I	Impervious		1	0.31 ± 0.31	0.05 ± 0.05
L T/C	Landscape Tree Canopy		0	0.00 ± 0.00	0.00 ± 0.00
LV	Low Vegetation		12	3.75 ± 1.06	0.60 ± 0.17
S/B	Soil / Bare Ground		1	0.31 ± 0.31	0.05 ± 0.05
S/G	Shadow / Gap		79	24.69 ± 2.41	3.95 ± 0.39
T	Forest Tree Canopy		223	69.69 ± 2.57	11.14 ± 0.41
T/G	Lawn		4	1.25 ± 0.63	0.20 ± 0.10
W	Water		0	0.00 ± 0.00	0.00 ± 0.00
Total			**320**	**100.00**	**15.99**

Arlington House Woodland – Succession Forest

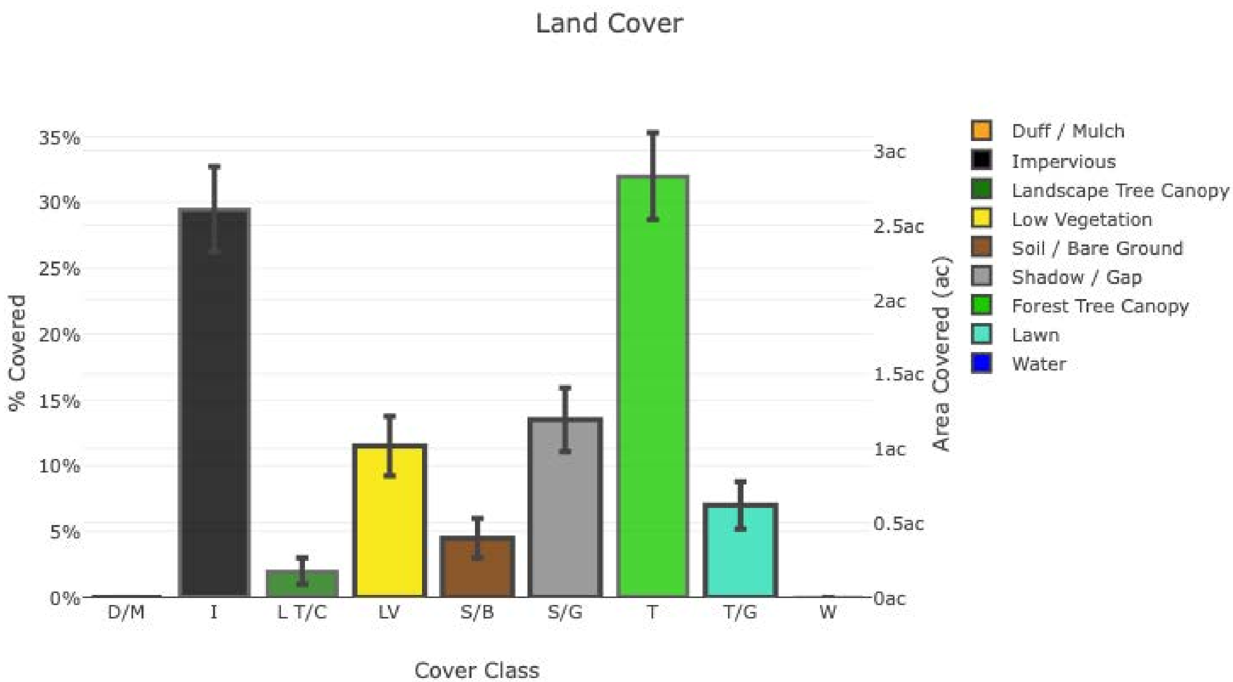

Figure 21. Tree canopy and land cover assessment of the Succession Forest within the Arlington House Woodland.

Table 10. Tree canopy and land cover assessment of the Succession Forest within the Arlington House Woodland.

Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
D/M	Duff / Mulch		0	0.00 ± 0.00	0.00 ± 0.00
I	Impervious		59	29.50 ± 3.22	2.61 ± 0.29
L T/C	Landscape Tree Canopy		4	2.00 ± 1.00	0.18 ± 0.09
LV	Low Vegetation		23	11.50 ± 2.26	1.02 ± 0.20
S/B	Soil / Bare Ground		9	4.50 ± 1.50	0.40 ± 0.13
S/G	Shadow / Gap		27	13.50 ± 2.42	1.19 ± 0.21
T	Forest Tree Canopy		64	32.00 ± 3.30	2.83 ± 0.29
T/G	Lawn		14	7.00 ± 1.80	0.62 ± 0.16
W	Water		0	0.00 ± 0.00	0.00 ± 0.00
Total			**200**	**100.00**	**8.85**

Table 11. Summarized tree canopy cover statistics for each of the three urban forests.

Theodore Roosevelt Island Tree Canopy Cover Statistics						
LANDSCAPE SUBDIVISIONS	**UPLAND**	**SUCCESSION**	**LOWLAND**	**WETLAND**	**MARSH**	**TOTAL**
TOTAL LAND AREA (acres)	40.86	17.96	16.34	17.30	5.50	**97.96**
TOTAL SAMPLE POINTS	798	340	320	340	100	1,898
FOREST TREE CANOPY POINTS	512	136	183	68	12	911
LANDSCAPE TREE CANOPY POINTS	0	2	0	15	2	19
TOTAL TREE CANOPY POINTS	512	138	183	83	14	930
CANOPY COVER (acres)	26.23	7.29	9.35	4.22	0.77	**47.90**
CANOPY COVER %	64.2%	40.6%	57.2%	24.4%	14.0%	**48.9%**

Columbia Island Tree Canopy Cover Statistics				
LANDSCAPE SUBDIVISIONS	**WOODLAND**	**SUCCESSION**	**PARKLAND**	**TOTAL**
TOTAL LAND AREA (acres)	34.47	13.97	81.25	**129.69**
TOTAL SAMPLE POINTS	700	280	1600	2580
FOREST TREE CANOPY POINTS	398	171	160	729
LANDSCAPE TREE CANOPY POINTS	49	14	159	222
TOTAL TREE CANOPY POINTS	447	185	319	951
CANOPY COVER (acres)	22.01	9.23	16.20	**47.44**
CANOPY COVER %	63.86%	66.07%	19.94%	**36.6%**

Arlington House Woodland Tree Canopy Cover Statistics			
LANDSCAPE SUBDIVISIONS	**UPLAND FOREST**	**SUCCESSION**	**TOTAL**
TOTAL LAND AREA (acres)	15.99	8.85	**24.84**
TOTAL SAMPLE POINTS	320	200	520
FOREST TREE CANOPY POINTS	223	64	287
LANDSCAPE TREE CANOPY POINTS	0	4	4
TOTAL TREE CANOPY POINTS	223	68	291
CANOPY COVER (acres)	11.14	3.01	**14.15**
CANOPY COVER %	69.69%	34%	**57.0%**

Step 5. Estimate Ecosystem Services of Tree Canopy

To estimate ecosystem services, i-Tree Canopy incorporates data for the acreage of the tree canopy assessed in the visual interpretation stage into complex computer models that use localized climate data and pollution data sourced from monitoring systems operated by government agencies and research organizations (Mills et al. 2015). The models combine the climate and pollution data with ecophysiological parameters for tree structure (e.g., leaf area) and function (e.g., photosynthesis, transpiration) that then translate tree canopy acreage into outputs of several regulating ecosystem services:

- Net primary productivity = photosynthesis driving carbon storage in structural carbohydrates of wood
- Gas exchange through foliage = carbon sequestration and gaseous air pollution absorption
- Dry and wet deposition on foliage = particulate air pollution interception
- Precipitation clinging to foliage and branches = rainfall interception and avoided runoff
- Evaporation from foliage and branches = returning precipitation water to the atmosphere
- Transpiration of water through the vascular system = moving water from the soil to the atmosphere

These models that relate tree canopy and ecophysiological functions to ecosystem services provide estimates of the quantity (carbon, pollution, stormwater) as well as the monetary worth of the ecosystem services (which are calculated in a variety of ways that look at the value of pollution avoidance to society).

For each urban forest site, we present below the outputs of the i-Tree Canopy models that estimated the ecosystem services of tree canopy (Tables 12 through 14). To simplify the reporting, we have combined and summed the data across all landscape subdivisions within each site. Therefore the ecosystem services are reported at the site level only. Each table shows the ecosystem service type, the annual rate of mitigation (except carbon storage, which is an estimate of lifetime accumulation of woody biomass by trees), and the annual value of mitigation (again, except for carbon storage, which is the present value of carbon that has been taken out of the atmosphere).

(continued on next page)

Theodore Roosevelt Island

Table 12. Summarized ecosystem services of tree canopy cover within Theodore Roosevelt Island.

Carbon Benefits						
Description	**Carbon (T)**	**SE**	**CO_2 equiv. (T)**	**SE**	**Value (USD)**	**SE**
Sequestered annually in trees	72	2.21	265	3.03	$12,308	$141
Stored in trees (Note: this benefit is not an annual rate)	1,641	0.39	6,015	68.98	$279,802	$3,209

Air Pollution Benefits						
Description	**Removal Rate (lb./ac./yr.)**	**Amount (lb.)**	**SE**	**Value Rate ($/lb./yr.)**	**Value ($)**	**SE**
Carbon monoxide removed annually	2.951	141.23	4.57	$0.70	$94.60	$3
Nitrogen dioxide removed annually	9.450	452.25	14.64	$0.70	$298.50	$10
Ozone removed annually	42.956	2,055.74	66.53	$4.76	$9,785.34	$317
Sulfur dioxide removed annually	4.801	229.76	7.44	$0.20	$43.66	$3
Particulate matter less than 2.5 microns removed annually	2.117	101.31	3.28	$217.50	$22,036.60	$713
Particulate matter greater than 2.5 microns and less than 10 microns removed annually	10.713	512.69	16.59	$3.10	$1,589.34	$51

Hydrological Benefits					
Description	**Effect Rate (Kgal./ac./yr.)**	**Amount (Kgal)**	**SE**	**Value (USD)**	**SE**
Avoided runoff	20.691	990.21	11.36	$8,852	$102
Evaporation	60.205	2,881.23	33.04	N/A	N/A
Interception	60.212	2,881.56	33.05	N/A	N/A
Transpiration	209.455	10,023.88	114.96	N/A	N/A
Potential evaporation	705.483	33,762.28	387.19	N/A	N/A
Potential evapotranspiration	515.221	24,656.91	282.77	N/A	N/A

N/A: A monetary value is not placed on these hydrological benefits by i-Tree Canopy.

Columbia Island

Table 13. Summarized ecosystem services of tree canopy cover within Columbia Island.

Carbon Benefits						
Description	**Carbon (T)**	**SE**	**CO_2 equiv. (T)**	**SE**	**Value (USD)**	**SE**
Sequestered annually in trees	72	1.28	262	4.69	$12,201	$116
Stored in trees (Note: this benefit is not an annual rate)	1,626	0.33	5,963	1.19	$277,369	$2,634

Air Pollution Benefits						
Description	**Removal Rate (lb./ac./yr.)**	**Amount (lb.)**	**SE**	**Value Rate ($/lb./yr.)**	**Value ($)**	**SE**
Carbon monoxide removed annually	2.951	140.00	1.33	$0.70	$93.80	$1
Nitrogen dioxide removed annually	9.450	448.32	4.26	$0.70	$295.90	$3
Ozone removed annually	42.956	2,037.87	19.36	$4.76	$9,700.28	$92
Sulfur dioxide removed annually	4.801	227.76	2.16	$0.20	$43.28	$4
Particulate matter less than 2.5 microns removed annually	2.117	100.43	0.95	$217.50	$21,845.10	$207
Particulate matter greater than 2.5 microns and less than 10 microns removed annually	10.713	508.23	4.83	$3.10	$1,575.13	15

Hydrological Benefits					
Description	**Effect Rate (Kgal./ac./yr.)**	**Amount (Kgal)**	**SE**	**Value (USD)**	**SE**
Avoided runoff	20.691	981.60	9.32	$8,776	$83.35
Evaporation	60.205	2,856.18	27.13	N/A	N/A
Interception	60.212	2,856.51	27.13	N/A	N/A
Transpiration	209.455	9,936.75	94.38	N/A	N/A
Potential evaporation	705.483	33,468.79	317.88	N/A	N/A
Potential evapotranspiration	515.221	24,442.58	282.77	N/A	N/A

N/A: A monetary value is not placed on these hydrological benefits by i-Tree Canopy.

Arlington House Woodland

Table 14. Summarized ecosystem services of tree canopy cover within Arlington House Woodland.

Carbon Benefits						
Description	Carbon (T)	SE	CO_2 equiv. (T)	SE	Value (USD)	SE
Sequestered annually in trees	21	0.33	78	0.12	$3,639	$79
Stored in trees (Note: this benefit is not an annual rate)	485	0.75	1,779	2.7	$82,742	$1,801

Air Pollution Benefits						
Description	Removal Rate (lb./ac./yr.)	Amount (lb.)	SE	Value Rate ($/lb./yr.)	Value ($)	SE
Carbon monoxide removed annually	2.951	41.76	0.91	$0.70	$28.00	$1
Nitrogen dioxide removed annually	9.450	133.74	2.91	$0.70	$88.30	$2
Ozone removed annually	42.956	607.91	13.23	$4.76	$2,893.67	$63
Sulfur dioxide removed annually	4.801	67.94	1.48	$0.20	$12.91	$0.28
Particulate matter less than 2.5 microns removed annually	2.117	29.96	0.65	$217.50	$6,516.60	$142
Particulate matter greater than 2.5 microns and less than 10 microns removed annually	10.713	151.61	3.30	$3.10	$469.68	$10

Hydrological Benefits					
Description	Effect Rate (Kgal./ac./yr.)	Amount (Kgal)	SE	Value (USD)	SE
Avoided runoff	20.691	292.82	6.37	$2,617	$57
Evaporation	60.205	852.02	18.55	N/A	N/A
Interception	60.212	852.12	18.55	N/A	N/A
Transpiration	209.455	2964.21	64.53	N/A	N/A
Potential evaporation	705.483	9984.02	217.35	N/A	N/A
Potential evapotranspiration	515.221	7291.42	158.73	N/A	N/A

N/A: A monetary value is not placed on these hydrological benefits by i-Tree Canopy.

Section III. Discussion of Findings and Limitations

Trends in Tree Canopy Across Sites and Landscape Types

At all three sites, those landscapes found in undisturbed upland locations had the greatest tree canopy percentages—averaging about 67%, or two-thirds of the land area. In successional landscapes, tree canopy percentages ranged from 34% to 66%. Within this range, lower canopy percentages were observed where disturbance had been more recent and the resulting gaps or low vegetation had not yet transitioned to overstory tree canopy. Tree canopy was progressively lower on Theodore Roosevelt Island as the landform transitioned to lower elevations of lowland, wetland, and marsh. As tree canopy diminished, low vegetation tended to increase across Theodore Roosevelt Island and Arlington House Woodland. On Columbia island, low vegetation and lawn were less prevalent than tree canopy, but lawn covered half of the area in the parkland landscape, and total canopy cover was about 20%, which illustrates the loose scattering of specimen trees and small groves intermixed with lawn and paved areas.

Total tree canopy was differentiated as forest tree canopy and landscape tree canopy to provide insights into fragmentation of the forest as well as prevalence of trees in proximity to people and infrastructure. On Theodore Roosevelt Island, forest tree canopy dominated regardless of landscape type. The general trend was that landscape tree canopy became more prevalent as landform transitioned to lower elevations. In the wetland and marsh, trees were limited to the sporadic dry hummocks, and there had been significant ash mortality from emerald ash borer, which fragmented the tree canopy and increased the prevalence of isolated landscape trees. On Columbia Island, forest tree canopy was prevalent in the woodland and succession forest, but landscape tree canopy was equally prevalent in the parkland, owing to the abundance of shade and ornamental trees established in cultural landscapes.

Columbia Island and Arlington House Woodland both had notable amounts of impervious surface (25% - 30% range). At Arlington House Woodland, this impervious surface was associated with concentrated construction on the northern edge of the succession forest. In contrast, impervious surfaces at Columbia Island were dispersed across the parkland as a network of roads, trails, and parking lots. It is important to note that impervious surface estimates across all three sites are conservative because the estimates only account for impervious unobstructed by overhead vegetation. There is likely additional impervious surface obscured by tall tree canopy.

At Arlington House Woodland, forest tree canopy accounted for all canopy in the upland forest landscape. Interestingly, one-quarter of the land area in the upland forest was shadow/gap—the highest percentage across any site in this assessment. This would be consistent with the old growth, uneven-aged character of the upland forest. Trees of varying heights and mortality-driven gaps are prevalent in old forests and were evident in this analysis. It is important to note that forest tree canopy likely comprised a portion of the shadow/gap percentage, but it was impossible to confidently identify it as tree canopy due to the lack of color contrast in the shadows. Perhaps a quarter to a half of this shadow/gap was actually tree canopy, and thus the estimate of forest tree canopy for Arlington House Woodland is a conservative estimate.

Trends in Ecosystem Services Across Sites and Landscape Types

Ecosystem services of tree canopy cover are estimated by i-Tree Canopy using regional multipliers for effect size (amount per unit of tree canopy) and value size (dollars per unit of tree canopy). In this

manner, i-Tree Canopy does not account for the composition of the tree canopy, that landscape that it occupies, or the ground that it covers. Quantitatively, there are no differences for any given acreage of tree canopy or its landscape type because i-Tree Canopy cannot differentiate the function of tree canopy across landscape types. As such, an acre of tree canopy on Theodore Roosevelt Island is calculated to have the same output of ecosystem services on Columbia Island and Arlington House Woodland. Yet, we intuitively know that an acre of canopy might function quite differently at each site based on differences in landscape type, canopy composition, and proximity of people and built environments. Some landscape types could be more or less effective for certain ecosystem services because the leaf configuration and leaf surface area comprising tree canopy might differ substantially across forest types, species assemblages, and age classes, which then affects evapotranspiration rates, gas exchange rates, photosynthesis rates, precipitation interception, and air pollution capture. Also, the stem density and tree basal area beneath the canopy might differ across landscape types, which would affect carbon sequestration and storage. Nonetheless, the outputs of i-Tree Canopy provide some insight into the magnitude and relative importance of several key ecosystem services and draw attention to the importance of tree canopy conservation for mitigating negative environmental effects of urbanization.

Across all three sites, the most economically valuable ecosystem services delivered annually by tree canopy were PM2.5 removal, carbon sequestration, ozone removal, and stormwater runoff avoidance. These monetary values represent the benefits to society of preventing the detrimental effect of air pollution, CO2 emissions and stormwater runoff. PM2.5 and ozone are air pollutants that arise from fossil fuel combustion and cause respiratory health problems for people. Stormwater runoff is the downhill flow of precipitation after it falls upon bare soil or impervious surfaces. This runoff often carries sediment and pollution into streams, rivers, and lakes that impairs the health of aquatic ecosystems and water quality for human consumption. In urban areas, this runoff also contributes to flash floods, which damage property and harm people.

Beyond these annual ecosystem services, the tree canopy represents a large population of trees that serve as an enormous sink for carbon storage. Carbon dioxide is absorbed from the atmosphere by leaves and converted to sugars through photosynthesis. The greater the leaf area in trees, the more carbon that is converted to sugars annually. About half of the sugar synthesis goes into structural carbohydrates of woody tree parts. These durable tissues accumulate as trees grow larger during their lives. This accumulation of carbon in trees through photosynthesis provides an important offset to carbon emissions into the atmosphere from combustion of fossil fuels. The analysis estimates that the trees found at these three sites store collectively about 3,752 tons of carbon.

Comparison to Chesapeake Conservancy Land Cover Data

To validate our analysis and share another approach to tree canopy assessment, we obtained land cover data from the Chesapeake Bay Program Land Use/Land Cover Data Project (Chesapeake Conservancy 2022). This dataset was generated using 1-meter resolution imagery obtained from the USDA's National Agriculture Imagery Program (NAIP) coupled with above-ground height information derived from LiDAR and local planimetric data (Claggett et al. 2022). The NAIP imagery was captured for Washington DC in 2017 and for Virginia in 2018.

The analytic approach to generating these data incorporates different technologies than were used in our assessment of the three GWMP urban forest sites. Specifically, computer software analyzes the spectral signature of each pixel comprising the 1-meter resolution imagery. Different types of land

cover have different spectral signatures that allow the computer software to differentiate them. The differentiation is enhanced by also using information about the height of the land cover using LiDAR and local planimetric data. By assigning every pixel in the imagery to a land cover class, the software generates a “wall-to-wall” landcover map.

In contrast the visual interpretation of aerial imagery performed in this case study using i-Tree Canopy only classified a representative sample of the area within an image and then used statistical methods to estimate tree canopy and land cover for the entire study area. So that is a tradeoff between the two methods – there is statistical uncertainty in our assessment method because we cannot classify every square meter in an image like the computer program in the Chesapeake assessment. The consequence of this sampling method is that photo interpretation is sensitive to classification inaccuracies when land cover types are patchy and clumpy because sample points might miss them, especially if the sample size of interpretation points is inadequate. However, the visual acuity of a human analyst looking at imagery is more precise in differentiating land cover. The human analyst in our assessment was viewing Google Earth Imagery with 15-cemtimeter resolution (about 45 times more detailed), and therefore could detect subtle differences in land cover that are obscured in 1-meter resolution imagery. As a result, the computer classification is likely to miss very small patches of one cover class surrounded by another. If a landscape is patchy, then the computer classification is more likely to miss small patches than a human analyst.

The Chesapeake assessment subdivides tree canopy into four different cover classes: (1) forest, (2) tree canopy over impervious surface, (3) tree canopy over turf grass, (4) tree canopy over all other surfaces. In the table below are shown the percentages of total land area for each of the tree canopy types at the urban forest sites we assessed. These statistics were generated through a GIS analysis of a raster map of the Chesapeake assessment data using the same boundaries for the sites used in our assessment. The raster maps are shown in Appendices 11 through 13.

Table 15. Percent of land area in each study site occupied by tree canopy cover based on 2017/2018 land use/land cover data obtained from the Chesapeake Conservancy.

Chesapeake Assessment of Tree Canopy (Percent of Land Area)			
Tree Canopy Cover Classes	**Roosevelt Island**	**Columbia Island**	**Arlington House Woodland**
Forest	73.1%	0.0%	75.6%
Tree Canopy Over Impervious Surface	3.5%	2.4%	2.1%
Tree Canopy Over Turf Grass	0.0%	0.3%	20.4%
Tree Canopy Over All Other Surfaces	13.6%	33.1%	0.0%
Total Of All Tree Canopy Cover	90.2%	35.8%	98.1%

Comparing the total tree canopy estimates from the Chesapeake Conservancy (Table 15) and the estimates from our current study (Table 11) reveals one commonality and two stark differences. The commonality occurs with the total tree canopy estimate for Columbia Island: our estimate was 37% tree canopy and the Chesapeake estimate was 36% tree canopy. This near match suggests that the two assessment methods have similar sensitivity and discernment of land cover types where tree spacing and canopy height are more uniform (resulting in fewer canopy gaps) in a designed park setting.

In contrast, the natural forest setting of Roosevelt Island and Arlington House Woodland resulted in stark differences between the two assessment methods. The Chesapeake assessment had much higher estimates of total tree canopy for Roosevelt Island (90% vs. 49%) and Arlington House Woodland (98% vs. 57%). Examining our visual interpretation data more closely can shed light on why these differences may exist. The obvious thing that stands out with our data is the high percentage of cover identified as canopy shadows and gaps. At Roosevelt Island, shadows/gaps accounted for between 2% and 20% of land cover, depending on the landscape type (Tables 1 – 5). Shadows/gaps were at the high end of this range in the two landscapes with a large acreage and high canopy cover: Upland Forest and Succession Forest. If shadows/gaps were assumed to be tree canopy, then the canopy cover estimates for those landscapes would rise to 84% and 60%, respectively. Similarly, Arlington House Woodland had high shadows/gaps frequency: 25% in the Upland Forest and 14% in the Succession Forest (Tables 9 and 10). If shadows/gaps were assumed to be tree canopy, then canopy cover estimates for those landscapes would rise to 95% and 48%, respectively.

Additionally, our visual interpretation was much more sensitive to detecting low vegetation (non-tree canopy) in small canopy gaps. Looking at the Chesapeake Bay land cover maps for Roosevelt Island (Appendix 11) and Arlington House Woodland (Appendix 13), very few patches of non-tree-canopy cover are visible within the large expanse of land classified as forest or tree canopy cover. Yet, visually examining the high-resolution imaged of Google Earth for Roosevelt Island (Figure 5) and Arlington House Woodland (Figure 9) suggests canopy gaps with low vegetation are more prevalent. This is especially the case for the Lowland Forest and Wetland Forest of Roosevelt Island. Our visual interpretation estimated that land cover occupied by low vegetation was 26% and 59% of these landscapes, respectively. The Chesapeake assessment map suggests that these two landscapes are nearly complete tree canopy except near the drainage channel. But the Google Earth image suggests otherwise. If low vegetation were considered tree canopy in our analysis, then total tree canopy would be 83% in the Lowland Forest and 84% in the Wetland Forest. One key distinction to keep in mind about the two assessments is that the Chesapeake assessment was based on 2017-2018 imagery and our assessment was based on 2022 imagery. There has been consider ash (Fraxinus spp.) mortality in the Lowland Forest and Wetland Forest in recent years due to emerald ash borer infestation. As a result, canopy gaps are much more evident in the recent imagery than the older imagery.

The implications of these differences in total tree canopy cover at Roosevelt Island and Arlington House Woodland are two-fold. First, our assessment should be considered a conservative estimate of tree canopy cover for the reasons described above. There is likely more tree biomass at each of these sites than our estimates would indicate if shadows/gaps we detected are indeed tree canopy. The other implication relates to ecosystem services of these urban forests. If the tree biomass estimate is conservative, then the ecosystem service estimates are likewise conservative. Carbon benefits of these urban forests are likely very conservative and could be as much as 46% underestimated based on the differences between the two assessments. It is not possible at this time to test the sensitivity of the two methods for accurately detecting true canopy gaps that result in less tree biomass. The true value likely exists somewhere between the extremes of the two assessments. That is, much of the canopy caps we detected are likely contiguous tree canopy, but also many of those gaps are likely real.

Limitations of Assessment Methods and Model Outputs

The ecosystem services (tree benefits) that are estimated by i-Tree Canopy are derived from mathematical models that use average characteristics of tree canopy structure and function for a given geographic area. Specifically, the software makes calculations using assumptions about a typical acre of tree canopy found in a typical mixed-land-use urban area. These assumptions include stem density (trees per acre), stem basal area (the biomass of trunks and branches based on tree size), crown volume (amount of leaf area below the surface of the canopy), photosynthesis and gas exchange rates (amount of carbon capture, air pollutant absorption, evapotranspiration), leaf size, and leaf morphology (amount of rainfall interception and avoided runoff).

A typical acre of the urban forest in mixed land use (trees intermixed with buildings and other gray infrastructure) has a quite different structure and function from not only a rural forest, but also urban forest fragments, and early succession urban forests (or those with a prevalence of ornamental rather than shade trees). As shown below (Figure 1), distinct forest types may have similar tree canopy cover (when viewed in two dimensions from above) yet have very different structures and functions below the canopy. As a result, these forest types deliver different quantities of ecosystem services for people and the environment despite looking very similar when viewed from above.

While i-Tree Canopy is a powerful tool for characterizing the amount of tree canopy in a study area, it does not currently possess the capability to estimate ecosystem services for varying forest canopy types. Within i-Tree Canopy, all tree cover is equivalent in terms of structure and function. Because the i-Tree Canopy model is parametrized for the average structure and function of the urban tree canopy, it does well at estimating ecosystem services of typical mixed-land-use urban forests, but may underestimate ecosystem services of forest fragments and may overestimate ecosystem services of early-succession and poorly structured urban forests.

Even though i-Tree Canopy derives ecosystem services based on the average canopy, we distinguish different landscape types, they are readily perceived by many people who experience the forest because these landscape types have different ecological characteristics. We suspect that such differentiation can help to improve the future management of forests. The proximity and accessibility of their sites allowed us to visit each one easily. In other sites, field inspection may not be possible or practical, but in this case, it allowed us to compare the satellite imagery with the observable difference in the field. In this way, it was a test to see how accurate the interpretation was.

Establishing a range of appropriate classes was more different than distinguishing landscape types because satellite imagery shows the canopy more clearly than it shows the ground. Identifying cover classes requires information about both the canopy and the ground layer, assumptions are necessary for the categorization of each cover class. In addition, the range of cover classes needs to account for the distinguish of conditions of the landscape but there are to be narrow enough to be an efficient methodology application.

Another aspect is the density of the random points surveyed in each landscape type. Originally, we studied each landscape type using 200 points per zone, as regards how large the landscape was. Later, we studied each landscape type and a constant density of 20 points/acre to establish a more rational methodology. We found that to define a correct density of random points we need more research/ development of this process into the advantages of greater or lesser density.

Section IV. Conclusion

This case study has provided an in-depth analysis of tree canopy cover and landscape typology of three important urban forest sites in the greater Washington D.C. area. To our knowledge, a detailed assessment of tree canopy and ecosystem services has never been performed for urban forests of the George Washington Memorial Parkway. Therefore, this assessment provides unprecedented insights into the character of the urban forest and its benefits to people and the environment. This case study has also demonstrated the feasibility of an assessment method that can be widely replicated throughout the GWMP and similar urban forest settings to generate data and insights useful for science, outreach, policy, and management. Comparison of our tree canopy cover estimates to a recent assessment for the same sites using alternate remote technology affirmed that our method is reliable for estimating tree canopy in park settings, but may underestimate tree canopy in forest settings. Further work is needed to evaluate the effects of canopy gaps/shadows on estimates of tree canopy cover in forest settings.

This case study has also highlighted the relationship between environmental characteristics and historic/cultural backgrounds. Theodore Roosevelt Island is mostly native vegetation, but around the memorial area, the upland forest is a cultural intervention. Columbia Island is a product of human intervention as it did not exist naturally, but has developed into an expansive urban ecosystem. In the Arlington House Woodland, we found a mature old-growth forest with extensive canopy, yet pressures of development and forces of disturbance acting around its perimeter to alter the structure and composition of the forest.

Keeping tree canopy intact, abundant, and healthy is critical for sustaining ecosystem services. Disturbance, pollution, and invasion by noxious pests are primary drivers of tree canopy degradation and loss in urban forests. Land development and construction cause forest fragmentation and physical injuries to trees that leave them vulnerable to drought stress, storm damage, and pest invasion. This disturbance is often compounded by the construction of impervious surfaces around trees, which disrupts water and nutrient cycling into the soil and intensifies heat stress in summer from hot pavement. While forest fragments and isolated trees often persist after disturbance, their ecosystem function and longevity may be compromised. A common outcome is that these vulnerable trees are overtaken by invasive plants and pests or succumb to the abiotic stress of heat, drought, and nutrient deficiency. When mature trees are lost, ecosystem services diminish considerably and decades are required to regain tree canopy from seedlings or transplanted trees. Worse yet, new trees that are either planted or naturally regenerate may not establish successfully and tree canopy is then displaced by invasive low vegetation or lawns.

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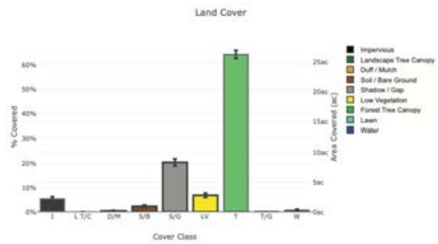
Appendix 1. i-Tree Canopy Output, Theodore Roosevelt Island – Upland Forest



Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
I	Impervious		43	5.39 ± 0.80	2.20 ± 0.33
L T/C	Landscape Tree Canopy		0	0.00 ± 0.00	0.00 ± 0.00
D/M	Duff / Mulch		3	0.38 ± 0.22	0.15 ± 0.09
S/B	Soil / Bare Ground		18	2.26 ± 0.53	0.92 ± 0.21
S/G	Shadow / Gap		162	20.30 ± 1.42	8.29 ± 0.58
LV	Low Vegetation		54	6.77 ± 0.89	2.76 ± 0.36
TC	Forest Tree Canopy		512	64.16 ± 1.70	26.21 ± 0.69
La	Lawn		0	0.00 ± 0.00	0.00 ± 0.00
W	Water		6	0.75 ± 0.31	0.31 ± 0.13
Total			**798**	**100.00**	**40.86**

Tree Benefit Estimates: Carbon (English units)

Description	Carbon (T)	±SE	CO_2 Equiv. (T)	±SE	Value (USD)	±SE
Sequestered annually in trees	39.52	±1.05	144.92	±3.83	$6,741	±178
Stored in trees (Note: this benefit is not an annual rate)	898.61	±23.77	3,294.90	±87.17	$153,258	±4,055

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Amount sequestered is based on 1.508 T of Carbon, or 5.529 T of CO_2, per ac/yr and rounded. Amount stored is based on 34.281 T of Carbon, or 125.697 T of CO_2, per ac and rounded. Value (USD) is based on $170.55/T of Carbon, or $46.51/T of CO_2 and rounded. (English units: T = tons (2,000 pounds), ac = acres)

Tree Benefit Estimates: Air Pollution (English units)

Abbr.	Description	Amount (lb)	±SE	Value (USD)	±SE
CO	Carbon Monoxide removed annually	77.37	±2.05	$52	±1
NO2	Nitrogen Dioxide removed annually	247.70	±6.55	$164	±4
O3	Ozone removed annually	1,126.00	±29.79	$5,359	±142
SO2	Sulfur Dioxide removed annually	125.84	±3.33	$23	±1
PM2.5	Particulate Matter less than 2.5 microns removed annually	55.48	±1.47	$12,069	±319
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	280.81	±7.43	$880	±23
Total		**1,913.21**	**±50.62**	**$18,547**	**±491**

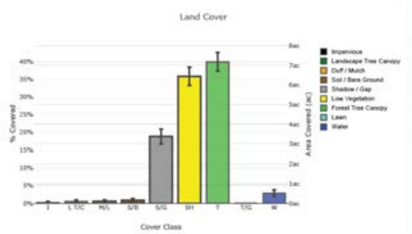
Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Air Pollution Estimates are based on these values in lb/ac/yr @ $/lb/yr and rounded:
CO 2.951 @ $0.67 | NO2 9.450 @ $0.66 | O3 42.956 @ $4.76 | SO2 4.801 @ $0.19 | PM2.5 2.117 @ $217.51 | PM10* 10.713 @ $3.13 (English units: lb = pounds, ac = acres)

Tree Benefit Estimates: Hydrological (English units)

Abbr.	Benefit	Amount (Kgal)	±SE	Value (USD)	±SE
AVRO	Avoided Runoff	542.38	±14.35	$4,847	±128
E	Evaporation	1,578.14	±41.75	N/A	N/A
I	Interception	1,578.33	±41.76	N/A	N/A
T	Transpiration	5,490.42	±145.26	N/A	N/A
PE	Potential Evaporation	18,492.79	±489.27	N/A	N/A
PET	Potential Evapotranspiration	13,505.45	±357.32	N/A	N/A

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Hydrological Estimates are based on these values in Kgal/ac/yr @ $/Kgal/yr and rounded:
AVRO 20.691 @ $8.94 | E 60.205 @ N/A | I 60.212 @ N/A | T 209.455 @ N/A | PE 705.483 @ N/A | PET 515.221 @ N/A (English units: Kgal = thousands of gallons, ac = acres)

Appendix 2. i-Tree Canopy Output, Theodore Roosevelt Island – Succession Forest



Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
I	Impervious		1	0.29 ± 0.29	0.05 ± 0.05
L T/C	Landscape Tree Canopy		2	0.59 ± 0.42	0.11 ± 0.07
D/M	Duff / Mulch		2	0.59 ± 0.42	0.11 ± 0.07
S/B	Soil / Bare Ground		3	0.88 ± 0.51	0.16 ± 0.09
S/G	Shadow / Gap		64	18.82 ± 2.12	3.38 ± 0.38
Lv	Low Vegetation		122	35.88 ± 2.60	6.44 ± 0.47
T	Forest Canopy		136	40.00 ± 2.66	7.18 ± 0.48
La	Lawn		0	0.00 ± 0.00	0.00 ± 0.00
W	Water		10	2.94 ± 0.92	0.53 ± 0.16
Total			**340**	**100.00**	**17.96**

Tree Benefit Estimates: Carbon (English units)

Description	Carbon (T)	±SE	CO_2 Equiv. (T)	±SE	Value (USD)	±SE
Sequestered annually in trees	10.99	±0.72	40.30	±2.64	$1,874	±123
Stored in trees (Note: this benefit is not an annual rate)	249.87	±16.40	916.21	±60.12	$42,616	±2,796

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Amount sequestered is based on 1.508 T of Carbon, or 5.529 T of CO_2, per ac/yr and rounded. Amount stored is based on 34.281 T of Carbon, or 125.697 T of CO_2, per ac and rounded. Value (USD) is based on $170.55/T of Carbon, or $46.51/T of CO_2 and rounded. (English units: T = tons (2,000 pounds), ac = acres)

Tree Benefit Estimates: Air Pollution (English units)

Abbr.	Description	Amount (lb)	±SE	Value (USD)	±SE
CO	Carbon Monoxide removed annually	21.51	±1.41	$14	±1
NO2	Nitrogen Dioxide removed annually	68.88	±4.52	$46	±3
O3	Ozone removed annually	313.11	±20.54	$1,490	±98
SO2	Sulfur Dioxide removed annually	34.99	±2.30	$6	±0
PM2.5	Particulate Matter less than 2.5 microns removed annually	15.43	±1.01	$3,356	±220
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	78.08	±5.12	$245	±16
Total		**532.00**	**±34.91**	**$5,157**	**±338**

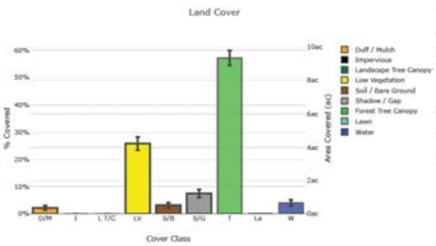
Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Air Pollution Estimates are based on these values in lb/ac/yr @ $/lb/yr and rounded:
CO 2.951 @ $0.67 | NO2 9.450 @ $0.66 | O3 42.956 @ $4.76 | SO2 4.801 @ $0.19 | PM2.5 2.117 @ $217.51 | PM10* 10.713 @ $3.13 (English units: lb = pounds, ac = acres)

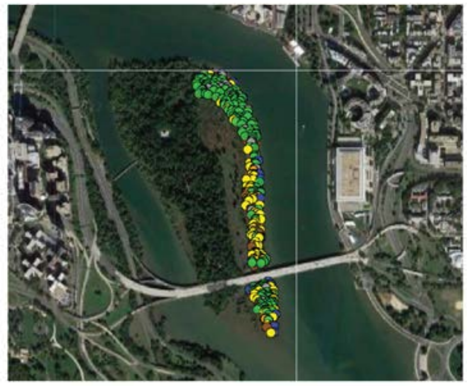
Tree Benefit Estimates: Hydrological (English units)

Abbr.	Benefit	Amount (Kgal)	±SE	Value (USD)	±SE
AVRO	Avoided Runoff	150.82	±9.90	$1,348	±88
E	Evaporation	438.83	±28.79	N/A	N/A
I	Interception	438.88	±28.80	N/A	N/A
T	Transpiration	1,526.71	±100.17	N/A	N/A
PE	Potential Evaporation	5,142.25	±337.40	N/A	N/A
PET	Potential Evapotranspiration	3,755.43	±246.41	N/A	N/A

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Hydrological Estimates are based on these values in Kgal/ac/yr @ $/Kgal/yr and rounded:
AVRO 20.691 @ $8.94 | E 60.205 @ N/A | I 60.212 @ N/A | T 209.455 @ N/A | PE 705.483 @ N/A | PET 515.221 @ N/A (English units: Kgal = thousands of gallons, ac = acres)

Appendix 3. i-Tree Canopy Output, Theodore Roosevelt Island – Lowland Forest





Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
D/M	Duff / Mulch		7	2.19 ± 0.83	0.36 ± 0.14
I	Impervious		0	0.00 ± 0.00	0.00 ± 0.00
L T/C	Landscape Tree Canopy		0	0.00 ± 0.00	0.00 ± 0.00
LV	Low Vegetation		83	25.94 ± 2.45	4.24 ± 0.40
S/B	Soil / Bare Ground		10	3.13 ± 0.97	0.51 ± 0.16
S/G	Shadow / Gap		24	7.50 ± 1.47	1.23 ± 0.24
T	Forest Tree Canopy		183	57.19 ± 2.77	9.35 ± 0.45
T/G	Lawn		0	0.00 ± 0.00	0.00 ± 0.00
W	Water		13	4.06 ± 1.10	0.66 ± 0.18
Total			**320**	**100.00**	**16.34**

Tree Benefit Estimates: Carbon (English units)

Description	Carbon (T)	±SE	CO_2 Equiv. (T)	±SE	Value (USD)	±SE
Sequestered annually in trees	14.09	±0.68	51.67	±2.50	$2,404	±116
Stored in trees (Note: this benefit is not an annual rate)	320.41	±15.50	1,174.85	±56.83	$54,647	±2,643

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Amount sequestered is based on 1.508 T of Carbon, or 5.529 T of CO_2, per ac/yr and rounded. Amount stored is based on 34.281 T of Carbon, or 125.697 T of CO_2, per ac and rounded. Value (USD) is based on $170.55/T of Carbon, or $46.51/T of CO_2 and rounded. (English units: T = tons (2,000 pounds), ac = acres)

Tree Benefit Estimates: Air Pollution (English units)

Abbr.	Description	Amount (lb)	±SE	Value (USD)	±SE
CO	Carbon Monoxide removed annually	27.59	±1.33	$18	±1
NO2	Nitrogen Dioxide removed annually	88.32	±4.27	$58	±3
O3	Ozone removed annually	401.50	±19.42	$1,911	±92
SO2	Sulfur Dioxide removed annually	44.87	±2.17	$8	±0
PM2.5	Particulate Matter less than 2.5 microns removed annually	19.78	±0.96	$4,303	±208
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	100.13	±4.84	$314	±15
Total		**682.19**	**±33.00**	**$6,613**	**±320**

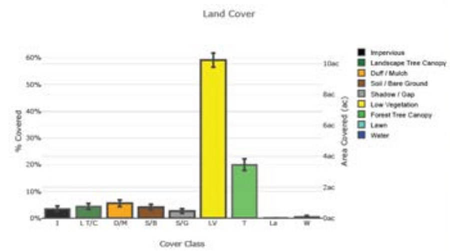
Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Air Pollution Estimates are based on these values in lb/ac/yr @ $/lb/yr and rounded:
CO 2.951 @ $0.67 | NO2 9.450 @ $0.66 | O3 42.956 @ $4.76 | SO2 4.801 @ $0.19 | PM2.5 2.117 @ $217.51 | PM10* 10.713 @ $3.13 (English units: lb = pounds, ac = acres)

Tree Benefit Estimates: Hydrological (English units)

Abbr.	Benefit	Amount (Kgal)	±SE	Value (USD)	±SE
AVRO	Avoided Runoff	193.40	±9.35	$1,728	±84
E	Evaporation	562.71	±27.22	N/A	N/A
I	Interception	562.78	±27.22	N/A	N/A
T	Transpiration	1,957.71	±94.69	N/A	N/A
PE	Potential Evaporation	6,593.93	±318.94	N/A	N/A
PET	Potential Evapotranspiration	4,815.61	±232.92	N/A	N/A

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Hydrological Estimates are based on these values in Kgal/ac/yr @ $/Kgal/yr and rounded:
AVRO 20.691 @ $8.94 | E 60.205 @ N/A | I 60.212 @ N/A | T 209.455 @ N/A | PE 705.483 @ N/A | PET 515.221 @ N/A (English units: Kgal = thousands of gallons, ac = acres)

Appendix 4. i-Tree Canopy Output, Theodore Roosevelt Island – Wetland Forest



Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
I	Impervious		12	3.53 ± 1.00	0.61 ± 0.17
L T/C	Landscape Tree Canopy		15	4.41 ± 1.11	0.76 ± 0.19
D/M	Duff / Mulch		19	5.59 ± 1.25	0.97 ± 0.22
S/B	Soil / Bare Ground		14	4.12 ± 1.08	0.71 ± 0.19
S/G	Shadow / Gap		9	2.65 ± 0.88	0.46 ± 0.15
LV	Low Vegetation		201	59.12 ± 2.67	10.23 ± 0.46
T	Forest Tree Canopy		68	20.00 ± 2.17	3.46 ± 0.38
La	Lawn		0	0.00 ± 0.00	0.00 ± 0.00
W	Water		2	0.59 ± 0.42	0.10 ± 0.07
Total			**340**	**100.00**	**17.30**

Tree Benefit Estimates: Carbon (English units)

Description	Carbon (T)	±SE	CO_2 Equiv. (T)	±SE	Value (USD)	±SE
Sequestered annually in trees	6.37	±0.61	23.35	±2.23	$1,086	±104
Stored in trees (Note: this benefit is not an annual rate)	144.77	±13.82	530.82	±50.66	$24,690	±2,356

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Amount sequestered is based on 1.508 T of Carbon, or 5.529 T of CO_2, per ac/yr and rounded. Amount stored is based on 34.281 T of Carbon, or 125.697 T of CO_2, per ac and rounded. Value (USD) is based on $170.55/T of Carbon, or $46.51/T of CO_2 and rounded. (English units: T = tons (2,000 pounds), ac = acres)

Tree Benefit Estimates: Air Pollution (English units)

Abbr.	Description	Amount (lb)	±SE	Value (USD)	±SE
CO	Carbon Monoxide removed annually	12.46	±1.19	$8	±1
NO2	Nitrogen Dioxide removed annually	39.91	±3.81	$26	±3
O3	Ozone removed annually	181.40	±17.31	$863	±82
SO2	Sulfur Dioxide removed annually	20.27	±1.93	$4	±0
PM2.5	Particulate Matter less than 2.5 microns removed annually	8.94	±0.85	$1,944	±186
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	45.24	±4.32	$142	±14
Total		**308.22**	**±29.41**	**$2,988**	**±285**

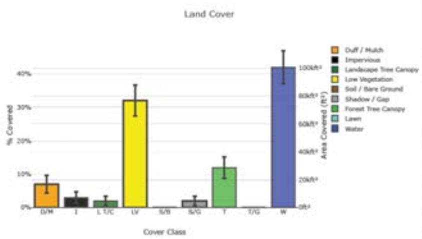
Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Air Pollution Estimates are based on these values in lb/ac/yr @ $/lb/yr and rounded:
CO 2.951 @ $0.67 | NO2 9.450 @ $0.66 | O3 42.956 @ $4.76 | SO2 4.801 @ $0.19 | PM2.5 2.117 @ $217.51 | PM10* 10.713 @ $3.13 (English units: lb = pounds, ac = acres)

Tree Benefit Estimates: Hydrological (English units)

Abbr.	Benefit	Amount (Kgal)	±SE	Value (USD)	±SE
AVRO	Avoided Runoff	87.38	±8.34	$781	±75
E	Evaporation	254.24	±24.26	N/A	N/A
I	Interception	254.27	±24.27	N/A	N/A
T	Transpiration	884.52	±84.41	N/A	N/A
PE	Potential Evaporation	2,979.24	±284.31	N/A	N/A
PET	Potential Evapotranspiration	2,175.77	±207.63	N/A	N/A

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Hydrological Estimates are based on these values in Kgal/ac/yr @ $/Kgal/yr and rounded:
AVRO 20.691 @ $8.94 | E 60.205 @ N/A | I 60.212 @ N/A | T 209.455 @ N/A | PE 705.483 @ N/A | PET 515.221 @ N/A (English units: Kgal = thousands of gallons, ac = acres)

Appendix 5. i-Tree Canopy Output, Theodore Roosevelt Island – Marsh



Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ft²) ± SE
D/M	Duff / Mulch		7	7.00 ± 2.65	16782.75 ± 6343.28
I	Impervious		3	3.00 ± 1.73	7192.61 ± 4152.65
L T/C	Landscape Tree Canopy		2	2.00 ± 1.41	4795.07 ± 3390.63
LV	Low Vegetation		32	32.00 ± 4.66	76721.16 ± 11183.93
S/B	Soil / Bare Ground		0	0.00 ± 0.00	0.00 ± 0.00
S/G	Shadow / Gap		2	2.00 ± 1.41	4795.07 ± 3390.63
T	Forest Tree Canopy		12	12.00 ± 3.25	28770.43 ± 7791.07
T/G	Lawn		0	0.00 ± 0.00	0.00 ± 0.00
W	Water		42	42.00 ± 4.94	100696.52 ± 11833.24
Total			**100**	**100.00**	**239753.62**

Tree Benefit Estimates: Carbon (English units)

Description	Carbon (T)	±SE	CO_2 Equiv. (T)	±SE	Value (USD)	±SE
Sequestered annually in trees	1.16	±0.29	4.26	±1.06	$198	±49
Stored in trees (Note: this benefit is not an annual rate)	26.42	±6.55	96.86	±24.01	$4,505	±1,117

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Amount sequestered is based on 0.000 T of Carbon, or 0.000 T of CO_2, per ft²/yr and rounded. Amount stored is based on 0.001 T of Carbon, or 0.003 T of CO_2, per ft² and rounded. Value (USD) is based on $170.55/T of Carbon, or $46.51/T of CO_2 and rounded. (English units: T = tons (2,000 pounds), ft² = square feet)

Tree Benefit Estimates: Air Pollution (English units)

Abbr.	Description	Amount (lb)	±SE	Value (USD)	±SE
CO	Carbon Monoxide removed annually	2.27	±0.56	$2	±0
NO2	Nitrogen Dioxide removed annually	7.28	±1.80	$5	±1
O3	Ozone removed annually	33.10	±8.20	$158	±39
SO2	Sulfur Dioxide removed annually	3.70	±0.92	$1	±0
PM2.5	Particulate Matter less than 2.5 microns removed annually	1.63	±0.40	$355	±88
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	8.25	±2.05	$26	±6
Total		**56.24**	**±13.94**	**$545**	**±135**

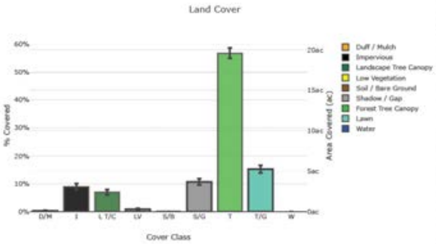
Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Air Pollution Estimates are based on these values in lb/ft²/yr @ $/lb/yr and rounded:
CO 0.000 @ $0.67 | NO2 0.000 @ $0.66 | O3 0.001 @ $4.76 | SO2 0.000 @ $0.19 | PM2.5 0.000 @ $217.51 | PM10* 0.000 @ $3.13 (English units: lb = pounds, ft² = square feet)

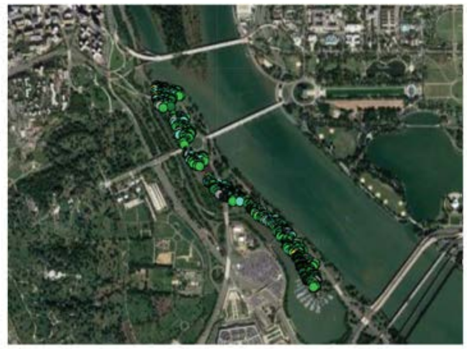
Tree Benefit Estimates: Hydrological (English units)

Abbr.	Benefit	Amount (Kgal)	±SE	Value (USD)	±SE
AVRO	Avoided Runoff	15.94	±3.95	$142	±35
E	Evaporation	46.39	±11.50	N/A	N/A
I	Interception	46.40	±11.50	N/A	N/A
T	Transpiration	161.40	±40.00	N/A	N/A
PE	Potential Evaporation	543.62	±134.73	N/A	N/A
PET	Potential Evapotranspiration	397.01	±98.40	N/A	N/A

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Hydrological Estimates are based on these values in Kgal/ft²/yr @ $/Kgal/yr and rounded:
AVRO 0.000 @ $8.94 | E 0.001 @ N/A | I 0.001 @ N/A | T 0.005 @ N/A | PE 0.016 @ N/A | PET 0.012 @ N/A (English units: Kgal = thousands of gallons, ft² = square feet)

Appendix 6. i-Tree Canopy Output, Columbia Island – Woodland





Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
D/M	Duff / Mulch		2	0.29 ± 0.20	0.10 ± 0.07
I	Impervious		63	9.00 ± 1.08	3.10 ± 0.37
L T/C	Landscape Tree Canopy		49	7.00 ± 0.96	2.41 ± 0.33
LV	Low Vegetation		6	0.86 ± 0.35	0.30 ± 0.12
S/B	Soil / Bare Ground		0	0.00 ± 0.00	0.00 ± 0.00
S/G	Shadow / Gap		75	10.71 ± 1.17	3.69 ± 0.40
T	Forest Tree Canopy		398	56.86 ± 1.87	19.60 ± 0.65
T/G	Lawn		107	15.29 ± 1.36	5.27 ± 0.47
W	Water		0	0.00 ± 0.00	0.00 ± 0.00
Total			**700**	**100.00**	**34.47**

Tree Benefit Estimates: Carbon (English units)

Description	Carbon (T)	±SE	CO_2 Equiv. (T)	±SE	Value (USD)	±SE
Sequestered annually in trees	33.19	±0.94	121.70	±3.46	$5,661	±161
Stored in trees (Note: this benefit is not an annual rate)	754.66	±21.46	2,767.07	±78.68	$128,707	±3,660

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Amount sequestered is based on 1.508 T of Carbon, or 5.529 T of CO_2, per ac/yr and rounded. Amount stored is based on 34.281 T of Carbon, or 125.697 T of CO_2, per ac and rounded. Value (USD) is based on $170.55/T of Carbon, or $46.51/T of CO_2 and rounded. (English units: T = tons (2,000 pounds), ac = acres)

Tree Benefit Estimates: Air Pollution (English units)

Abbr.	Description	Amount (lb)	±SE	Value (USD)	±SE
CO	Carbon Monoxide removed annually	64.97	±1.85	$43	±1
NO2	Nitrogen Dioxide removed annually	208.02	±5.92	$137	±4
O3	Ozone removed annually	945.62	±26.89	$4,501	±128
SO2	Sulfur Dioxide removed annually	105.68	±3.01	$20	±1
PM2.5	Particulate Matter less than 2.5 microns removed annually	46.60	±1.32	$10,135	±288
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	235.82	±6.71	$739	±21
Total		**1,606.72**	**±45.69**	**$15,576**	**±443**

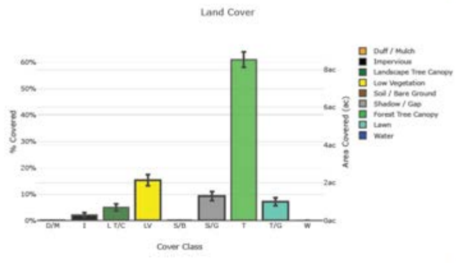
Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Air Pollution Estimates are based on these values in lb/ac/yr @ $/lb/yr and rounded:
CO 2.951 @ $0.67 | NO2 9.450 @ $0.66 | O3 42.956 @ $4.76 | SO2 4.801 @ $0.19 | PM2.5 2.117 @ $217.51 | PM10* 10.713 @ $3.13 (English units: lb = pounds, ac = acres)

Tree Benefit Estimates: Hydrological (English units)

Abbr.	Benefit	Amount (Kgal)	±SE	Value (USD)	±SE
AVRO	Avoided Runoff	455.50	±12.95	$4,070	±116
E	Evaporation	1,325.33	±37.69	N/A	N/A
I	Interception	1,325.49	±37.69	N/A	N/A
T	Transpiration	4,610.88	±131.11	N/A	N/A
PE	Potential Evaporation	15,530.34	±441.61	N/A	N/A
PET	Potential Evapotranspiration	11,341.95	±322.51	N/A	N/A

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Hydrological Estimates are based on these values in Kgal/ac/yr @ $/Kgal/yr and rounded:
AVRO 20.691 @ $8.94 | E 60.205 @ N/A | I 60.212 @ N/A | T 209.455 @ N/A | PE 705.483 @ N/A | PET 515.221 @ N/A (English units: Kgal = thousands of gallons, ac = acres)

Appendix 7. i-Tree Canopy Output, Columbia Island – Succession Forest



Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
D/M	Duff / Mulch		0	0.00 ± 0.00	0.00 ± 0.00
I	Impervious		6	2.14 ± 0.87	0.30 ± 0.12
L T/C	Landscape Tree Canopy		14	5.00 ± 1.30	0.70 ± 0.18
LV	Low Vegetation		43	15.36 ± 2.15	2.15 ± 0.30
S/B	Soil / Bare Ground		0	0.00 ± 0.00	0.00 ± 0.00
S/G	Shadow / Gap		26	9.29 ± 1.73	1.30 ± 0.24
T	Forest Tree Canopy		171	61.07 ± 2.91	8.53 ± 0.41
T/G	Lawn		20	7.14 ± 1.54	1.00 ± 0.22
W	Water		0	0.00 ± 0.00	0.00 ± 0.00
Total			**280**	**100.00**	**13.97**

Tree Benefit Estimates: Carbon (English units)

Description	Carbon (T)	±SE	CO_2 Equiv. (T)	±SE	Value (USD)	±SE
Sequestered annually in trees	13.92	±0.60	51.05	±2.19	$2,374	±102
Stored in trees (Note: this benefit is not an annual rate)	316.52	±13.56	1,160.58	±49.70	$53,983	±2,312

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Amount sequestered is based on 1.508 T of Carbon, or 5.529 T of CO_2, per ac/yr and rounded. Amount stored is based on 34.281 T of Carbon, or 125.697 T of CO_2, per ac and rounded. Value (USD) is based on $170.55/T of Carbon, or $46.51/T of CO_2 and rounded. (English units: T = tons (2,000 pounds), ac = acres)

Tree Benefit Estimates: Air Pollution (English units)

Abbr.	Description	Amount (lb)	±SE	Value (USD)	±SE
CO	Carbon Monoxide removed annually	27.25	±1.17	$18	±1
NO2	Nitrogen Dioxide removed annually	87.25	±3.74	$58	±2
O3	Ozone removed annually	396.62	±16.99	$1,888	±81
SO2	Sulfur Dioxide removed annually	44.33	±1.90	$8	±0
PM2.5	Particulate Matter less than 2.5 microns removed annually	19.54	±0.84	$4,251	±182
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	98.91	±4.24	$310	±13
Total		**673.90**	**±28.86**	**$6,533**	**±280**

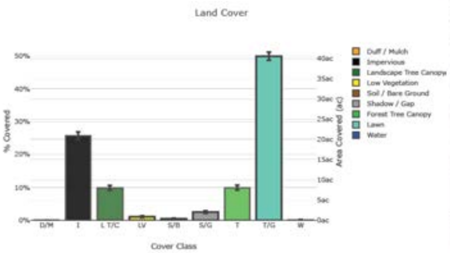
Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Air Pollution Estimates are based on these values in lb/ac/yr @ $/lb/yr and rounded:
CO 2.951 @ $0.67 | NO2 9.450 @ $0.66 | O3 42.956 @ $4.76 | SO2 4.801 @ $0.19 | PM2.5 2.117 @ $217.51 | PM10* 10.713 @ $3.13 (English units: lb = pounds, ac = acres)

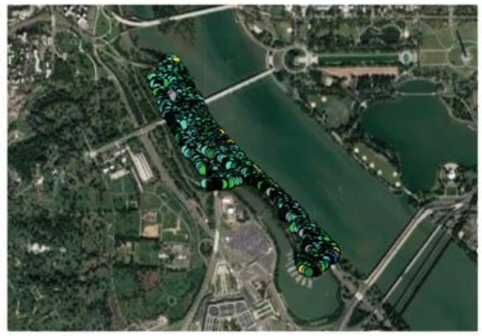
Tree Benefit Estimates: Hydrological (English units)

Abbr.	Benefit	Amount (Kgal)	±SE	Value (USD)	±SE
AVRO	Avoided Runoff	191.05	±8.18	$1,707	±73
E	Evaporation	555.88	±23.81	N/A	N/A
I	Interception	555.94	±23.81	N/A	N/A
T	Transpiration	1,933.92	±82.82	N/A	N/A
PE	Potential Evaporation	6,513.80	±278.95	N/A	N/A
PET	Potential Evapotranspiration	4,757.09	±203.72	N/A	N/A

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Hydrological Estimates are based on these values in Kgal/ac/yr @ $/Kgal/yr and rounded:
AVRO 20.691 @ $8.94 | E 60.205 @ N/A | I 60.212 @ N/A | T 209.455 @ N/A | PE 705.483 @ N/A | PET 515.221 @ N/A (English units: Kgal = thousands of gallons, ac = acres)

Appendix 8. i-Tree Canopy Output, Columbia Island – Parkland





Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
D/M	Duff / Mulch		0	0.00 ± 0.00	0.00 ± 0.00
I	Impervious		412	25.75 ± 1.09	20.92 ± 0.89
L T/C	Landscape Tree Canopy		159	9.94 ± 0.75	8.07 ± 0.61
LV	Low Vegetation		18	1.13 ± 0.26	0.91 ± 0.21
S/B	Soil / Bare Ground		8	0.50 ± 0.18	0.41 ± 0.14
S/G	Shadow / Gap		41	2.56 ± 0.40	2.08 ± 0.32
T	Forest Tree Canopy		160	10.00 ± 0.75	8.12 ± 0.61
T/G	Lawn		800	50.00 ± 1.25	40.62 ± 1.02
W	Water		2	0.13 ± 0.09	0.10 ± 0.07
Total			1600	100.00	81.25

Tree Benefit Estimates: Carbon (English units)

Description	Carbon (T)	±SE	CO_2 Equiv. (T)	±SE	Value (USD)	±SE
Sequestered annually in trees	24.42	±1.22	89.56	±4.49	$4,166	±209
Stored in trees (Note: this benefit is not an annual rate)	555.33	±27.82	2,036.20	±102.01	$94,711	±4,745

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Amount sequestered is based on 1.508 T of Carbon, or 5.529 T of CO_2, per ac/yr and rounded. Amount stored is based on 34.281 T of Carbon, or 125.697 T of CO_2, per ac and rounded. Value (USD) is based on $170.55/T of Carbon, or $46.51/T of CO_2 and rounded. (English units: T = tons (2,000 pounds), ac = acres)

Tree Benefit Estimates: Air Pollution (English units)

Abbr.	Description	Amount (lb)	±SE	Value (USD)	±SE
CO	Carbon Monoxide removed annually	47.81	±2.40	$32	±2
NO2	Nitrogen Dioxide removed annually	153.08	±7.67	$101	±5
O3	Ozone removed annually	695.85	±34.86	$3,312	±166
SO2	Sulfur Dioxide removed annually	77.77	±3.90	$14	±1
PM2.5	Particulate Matter less than 2.5 microns removed annually	34.29	±1.72	$7,458	±374
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	173.54	±8.69	$544	±27
Total		1,182.34	±59.23	$11,462	±574

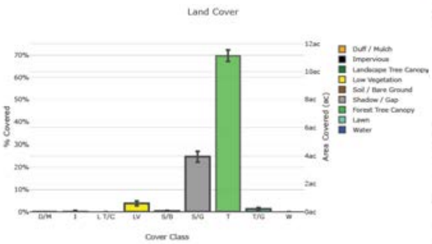
Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Air Pollution Estimates are based on these values in lb/ac/yr @ $/lb/yr and rounded:
CO 2.951 @ $0.67 | NO2 9.450 @ $0.66 | O3 42.956 @ $4.76 | SO2 4.801 @ $0.19 | PM2.5 2.117 @ $217.51 | PM10* 10.713 @ $3.13 (English units: lb = pounds, ac = acres)

Tree Benefit Estimates: Hydrological (English units)

Abbr.	Benefit	Amount (Kgal)	±SE	Value (USD)	±SE
AVRO	Avoided Runoff	335.18	±16.79	$2,995	±150
E	Evaporation	975.27	±48.86	N/A	N/A
I	Interception	975.38	±48.86	N/A	N/A
T	Transpiration	3,393.00	±169.98	N/A	N/A
PE	Potential Evaporation	11,428.27	±572.53	N/A	N/A
PET	Potential Evapotranspiration	8,346.17	±418.13	N/A	N/A

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Hydrological Estimates are based on these values in Kgal/ac/yr @ $/Kgal/yr and rounded:
AVRO 20.691 @ $8.94 | E 60.205 @ N/A | I 60.212 @ N/A | T 209.455 @ N/A | PE 705.483 @ N/A | PET 515.221 @ N/A (English units: Kgal = thousands of gallons, ac = acres)

Appendix 9. i-Tree Canopy Output, Arlington House Woodland – Upland Forest



Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
D/M	Duff / Mulch		0	0.00 ± 0.00	0.00 ± 0.00
I	Impervious		1	0.31 ± 0.31	0.05 ± 0.05
L T/C	Landscape Tree Canopy		0	0.00 ± 0.00	0.00 ± 0.00
LV	Low Vegetation		12	3.75 ± 1.06	0.60 ± 0.17
S/B	Soil / Bare Ground		1	0.31 ± 0.31	0.05 ± 0.05
S/G	Shadow / Gap		79	24.69 ± 2.41	3.95 ± 0.39
T	Forest Tree Canopy		223	69.69 ± 2.57	11.14 ± 0.41
T/G	Lawn		4	1.25 ± 0.63	0.20 ± 0.10
W	Water		0	0.00 ± 0.00	0.00 ± 0.00
Total			**320**	**100.00**	**15.99**

Tree Benefit Estimates: Carbon (English units)

Description	Carbon (T)	±SE	CO_2 Equiv. (T)	±SE	Value (USD)	±SE
Sequestered annually in trees	16.80	±0.62	61.59	±2.27	$2,865	±106
Stored in trees (Note: this benefit is not an annual rate)	381.91	±14.08	1,400.34	±51.63	$65,135	±2,401

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Amount sequestered is based on 1.508 T of Carbon, or 5.529 T of CO_2, per ac/yr and rounded. Amount stored is based on 34.281 T of Carbon, or 125.697 T of CO_2, per ac and rounded. Value (USD) is based on $170.55/T of Carbon, or $46.51/T of CO_2 and rounded. (English units: T = tons (2,000 pounds), ac = acres)

Tree Benefit Estimates: Air Pollution (English units)

Abbr.	Description	Amount (lb)	±SE	Value (USD)	±SE
CO	Carbon Monoxide removed annually	32.88	±1.21	$22	±1
NO2	Nitrogen Dioxide removed annually	105.27	±3.88	$70	±3
O3	Ozone removed annually	478.56	±17.64	$2,278	±84
SO2	Sulfur Dioxide removed annually	53.48	±1.97	$10	±0
PM2.5	Particulate Matter less than 2.5 microns removed annually	23.58	±0.87	$5,129	±189
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	119.34	±4.40	$374	±14
Total		**813.12**	**±29.98**	**$7,882**	**±291**

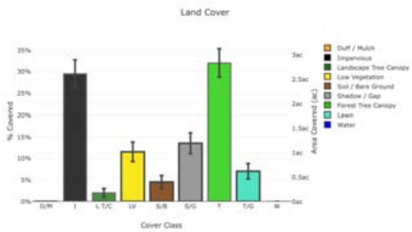
Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Air Pollution Estimates are based on these values in lb/ac/yr @ $/lb/yr and rounded:
CO 2.951 @ $0.67 | NO2 9.450 @ $0.66 | O3 42.956 @ $4.76 | SO2 4.801 @ $0.19 | PM2.5 2.117 @ $217.51 | PM10* 10.713 @ $3.13 (English units: lb = pounds, ac = acres)

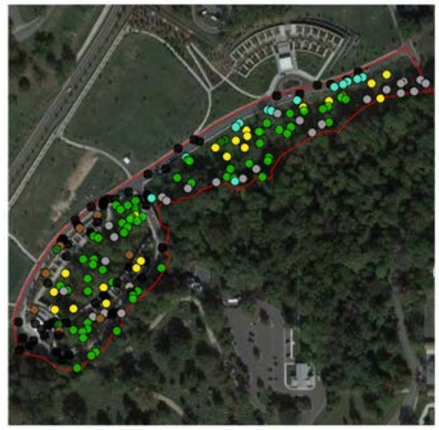
Tree Benefit Estimates: Hydrological (English units)

Abbr.	Benefit	Amount (Kgal)	±SE	Value (USD)	±SE
AVRO	Avoided Runoff	230.51	±8.50	$2,060	±76
E	Evaporation	670.72	±24.73	N/A	N/A
I	Interception	670.79	±24.73	N/A	N/A
T	Transpiration	2,333.45	±86.03	N/A	N/A
PE	Potential Evaporation	7,859.50	±289.77	N/A	N/A
PET	Potential Evapotranspiration	5,739.87	±211.62	N/A	N/A

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Hydrological Estimates are based on these values in Kgal/ac/yr @ $/Kgal/yr and rounded:
AVRO 20.691 @ $8.94 | E 60.205 @ N/A | I 60.212 @ N/A | T 209.455 @ N/A | PE 705.483 @ N/A | PET 515.221 @ N/A (English units: Kgal = thousands of gallons, ac = acres)

Appendix 10. i-Tree Canopy Output, Arlington House Woodland – Succession Forest





Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (ac) ± SE
D/M	Duff / Mulch		0	0.00 ± 0.00	0.00 ± 0.00
I	Impervious		59	29.50 ± 3.22	2.61 ± 0.29
L T/C	Landscape Tree Canopy		4	2.00 ± 1.00	0.18 ± 0.09
LV	Low Vegetation		23	11.50 ± 2.26	1.02 ± 0.20
S/B	Soil / Bare Ground		9	4.50 ± 1.50	0.40 ± 0.13
S/G	Shadow / Gap		27	13.50 ± 2.42	1.19 ± 0.21
T	Forest Tree Canopy		64	32.00 ± 3.30	2.83 ± 0.29
T/G	Lawn		14	7.00 ± 1.80	0.62 ± 0.16
W	Water		0	0.00 ± 0.00	0.00 ± 0.00
Total			**200**	**100.00**	**8.85**

Tree Benefit Estimates: Carbon (English units)

Description	Carbon (T)	±SE	CO_2 Equiv. (T)	±SE	Value (USD)	±SE
Sequestered annually in trees	4.54	±0.45	16.63	±1.64	$774	±76
Stored in trees (Note: this benefit is not an annual rate)	103.14	±10.16	378.18	±37.26	$17,591	±1,733

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Amount sequestered is based on 1.508 T of Carbon, or 5.529 T of CO_2, per ac/yr and rounded. Amount stored is based on 34.281 T of Carbon, or 125.697 T of CO_2, per ac and rounded. Value (USD) is based on $170.55/T of Carbon, or $46.51/T of CO_2 and rounded. (English units: T = tons (2,000 pounds), ac = acres)

Tree Benefit Estimates: Air Pollution (English units)

Abbr.	Description	Amount (lb)	±SE	Value (USD)	±SE
CO	Carbon Monoxide removed annually	8.88	±0.87	$6	±1
NO2	Nitrogen Dioxide removed annually	28.43	±2.80	$19	±2
O3	Ozone removed annually	129.24	±12.73	$615	±61
SO2	Sulfur Dioxide removed annually	14.44	±1.42	$3	±0
PM2.5	Particulate Matter less than 2.5 microns removed annually	6.37	±0.63	$1,385	±136
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	32.23	±3.18	$101	±10
Total		**219.59**	**±21.63**	**$2,129**	**±210**

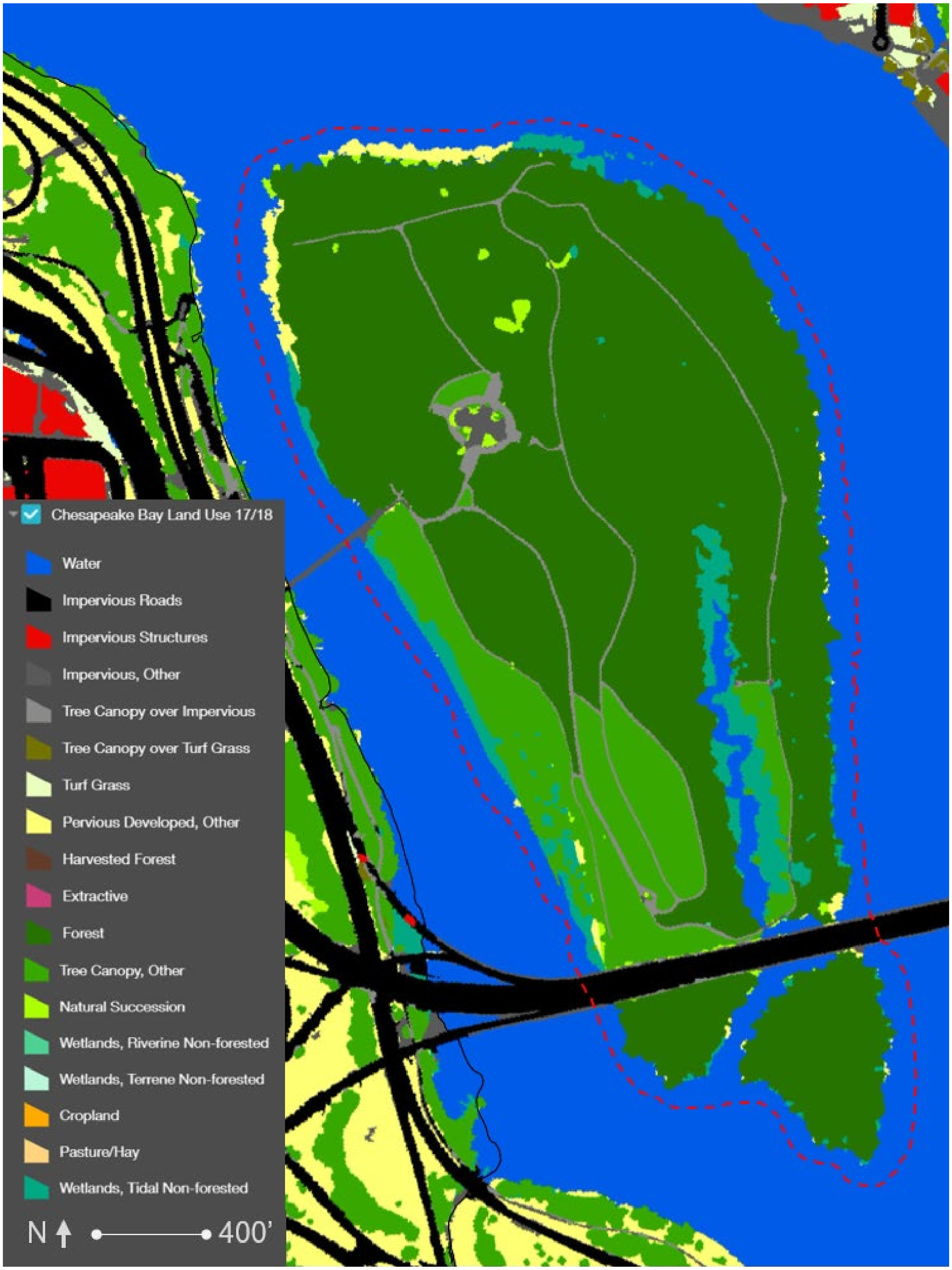
Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Air Pollution Estimates are based on these values in lb/ac/yr @ $/lb/yr and rounded:
CO 2.951 @ $0.67 | NO2 9.450 @ $0.66 | O3 42.956 @ $4.76 | SO2 4.801 @ $0.19 | PM2.5 2.117 @ $217.51 | PM10* 10.713 @ $3.13 (English units: lb = pounds, ac = acres)

Tree Benefit Estimates: Hydrological (English units)

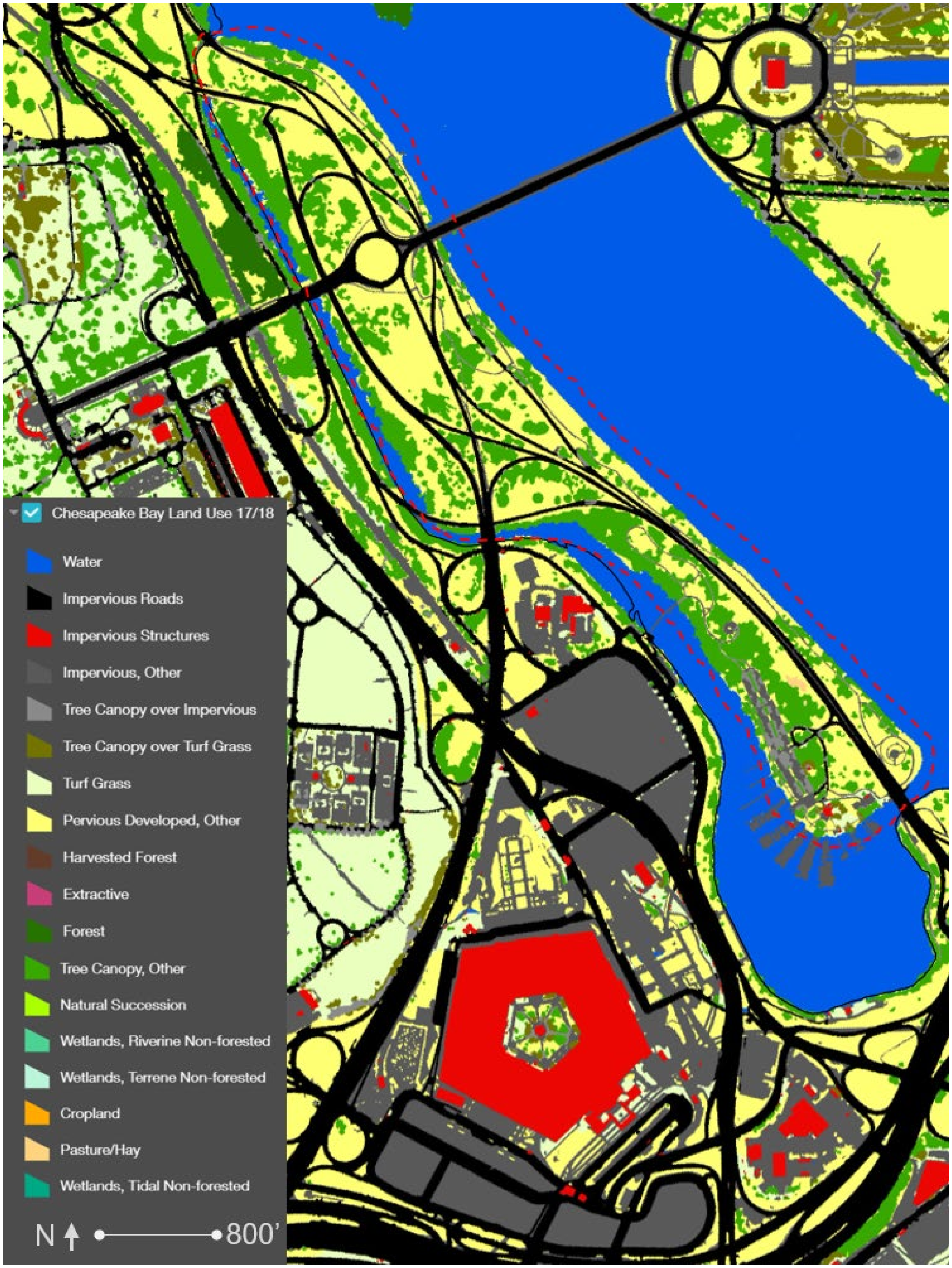
Abbr.	Benefit	Amount (Kgal)	±SE	Value (USD)	±SE
AVRO	Avoided Runoff	62.25	±6.13	$556	±55
E	Evaporation	181.13	±17.85	N/A	N/A
I	Interception	181.16	±17.85	N/A	N/A
T	Transpiration	630.18	±62.08	N/A	N/A
PE	Potential Evaporation	2,122.55	±209.11	N/A	N/A
PET	Potential Evapotranspiration	1,550.12	±152.72	N/A	N/A

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Hydrological Estimates are based on these values in Kgal/ac/yr @ $/Kgal/yr and rounded:
AVRO 20.691 @ $8.94 | E 60.205 @ N/A | I 60.212 @ N/A | T 209.455 @ N/A | PE 705.483 @ N/A | PET 515.221 @ N/A (English units: Kgal = thousands of gallons, ac = acres)

Appendix 11. Screen capture of land cover map for Roosevelt Island generated from computerized classification of 1-m resolution aerial imagery (National Agriculture Imagery) by the Chesapeake Conservancy (https://www.chesapeakeconservancy.org/conservation-innovation-center/high-resolution-data/lulc-data-project-2022)



Appendix 12. Screen capture of land cover map for Columbia Island generated from computerized classification of 1-m resolution aerial imagery (National Agriculture Imagery) by the Chesapeake Conservancy (https://www.chesapeakeconservancy.org/conservation-innovation-center/high-resolution-data/lulc-data-project-2022)



Appendix 13. Screen capture of land cover map for Arlington House Woodland generated from computerized classification of 1-m resolution aerial imagery (National Agriculture Imagery) by the Chesapeake Conservancy (https://www.chesapeakeconservancy.org/conservation-innovation-center/high-resolution-data/lulc-data-project-2022)