Mapping & Managing Urban Ecosystems

A summary of the 2018-2019 Urban Ecosystems graduate internship & methodology case study from Seattle Public Utilities Urban Ecosystems group

MEH Project Report Final Draft

In partial fulfillment of the Master of Environmental Horticulture degree program

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Above: Anna's Hummingbird *(Calypte anna)* surveying the "urban ecosystem" from a razor wire perch

Cover Image: Great Blue Heron fishing at a Meadowbrook Pond, an engineered stormwater detention pond owned and managed by Seattle Public Utilities.

(*photo credits: Scott Brekke Davis*)

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Acknowledgements

This internship and case study would not have been possible without the contributions of many individuals.

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Internship Summary

In Spring of 2018 I was accepted into the Urban Ecosystems graduate student internship program offered by Seattle Public Utilities (SPU), a municipal utility company in Seattle, Washington. The internship offered an opportunity for applied experiences and skill development in vegetation management, habitat monitoring, and other practices related to ecological restoration. I applied for this internship in pursuit of a satisfactory project for the partial fulfillment of the Master of Environmental Horticulture (MEH) degree. At the time of this writing I have worked within the internship program for roughly 600 hours over 10 months. In this summary I will outline the activities of the internship program that were relevant to the goals of the MEH program. Following this summary of my activities, I provide a technical report covering the project to which I devoted the majority of my time, which was specifically the creation of digital maps utilizing Geographic Information Systems (GIS), and analyses of ecosystem services provided by trees on SPU properties. The maps serve two primary purposes for SPU: site management and ecosystem analysis. The mapping project as presented here focuses on the ecosystem analysis component of the project, and is presented in the format of a technical report, including project background, methodology, results, and discussion.

Within the Urban Ecosystems internship program, I had the opportunity to participate in three major activities that were relevant to environmental horticulture and ecological restoration, which are the two broad knowledge areas of the MEH degree program. Those three activities are stream habitat monitoring, mitigation planning and execution, and the creation of digital maps for the purposes of vegetation and project management. All of the activities took place within an urban context, the city of Seattle specifically. Each of these activities will be covered in the following sections.

Stream Habitat Monitoring

Stream habitat monitoring included setting seines for reach-segmentation, electrofishing, fish species identification, and the collection of biological data on salmonids. Reach segmentation was for the purpose of consistency in data collection over many assessments. The process requires the setting of seines (fishing nets) at either end of the study-reach in order to temporarily block fish passage. Each reach segment was then “electrofished”, which requires researchers to be in the stream while repeatedly applying electric shocks to the water, in order to stun, locate, and capture fish. Biological assessments involved anesthetizing fish, measuring fish length, extracting stomach contents with gastric lavage, and installing electronic tracking devices on a sample of the collected fish. These assessments were part of multiple ongoing research and monitoring efforts. Six years prior, these urban creek systems and associated flood plains had also been extensively restored by SPU, in part due to localized flooding and erosion

Figure i: Two members of the SPU Urban Ecosystems team electrofish the Kingfisher reach of Thorton Creek for biological data collection associated with post-restoration stream habitat surveys

problems in the Thornton Creek watershed, an urban and highly developed watershed within northeast Seattle. Project sites for stream habitat monitoring included Meadowbrook Pond, the Confluence, and Kingfisher Natural Area, all of which are segments of the Thornton Creek watershed.

Mitigation Planning & Execution

Mitigation planning and execution involved assessing future project sites, assisting in species selection for plantings, installation of plants, and assisting volunteer work events. I was introduced to completed restoration project sites, involved in an ongoing restoration site, and helped survey a future project site. Assistance with species selection required assessing site conditions and recommending practical native species that are locally available.

Digital Map Creation

The creation of digital maps included an extensive effort to collect physical data on vegetation within SPU properties, particularly trees, including species identification, tree height, canopy width, and stem diameter. This data was coupled with the creation of digital maps utilizing ArcGIS and ArcGIS Collector (ESRI 2012).

My participation in the mapping project was during the initial testing phases of the methodology design. I would like to emphasize that I was part of, and assigned to, a team that had already designed the project goals and initial methods prior to my hiring. I worked primarily in conjunction with my supervisor, Josh Meidav, senior environmental analyst at SPU, and we met regularly with our technical support, Lynne Ashton and John Edwards, who serve as GIS analysts for Seattle Information Technology. I contributed to the project largely through field preliminary site analysis, field data collection, and data quality control and analysis. I also contributed to decisions on how to adapt the methodology after initial testing. Other individuals involved with this report are acknowledged on the Acknowledgements page. The mapping effort will continue after the completion of my internship, and therefore this report is documenting a case study within a larger project. Consequently, the reader should be aware that certain aspects of the project were designed in a way that limits the explanatory power of any data that was produced by the study. This limitation will be discussed in more detail within the report.

Figure ii: Report author and Urban Ecosystems intern, Scott Brekke Davis, prepared with data sheet, tablet, and high-vis forestry vest for field data collection for the Mapping Urban Ecosystems project.

Technical Report

Mapping and Evaluating Vegetation in an Urban Ecosystem

a methodology case study from Seattle Public Utilities' Urban Ecosystems group

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Abstract: Urbanization and suburban sprawl are global phenomena that have contributed significantly to environmental degradation and habitat loss. Terrestrial and aquatic ecosystems in urban environments are typically degraded and highly altered, and "natural spaces" in urban areas are often separated by large distances due to the extensive and intensive development of built-environments. The positive function and value provided by urban ecosystems is often difficult to quantify, and management can be difficult as a result of existing degradation and disconnection. Two primary methodologies are used for surveying these disconnected urban environments; ground-based observations and remote sensing, and both of these methodologies are benefitting from new technologies. This study focuses on demonstrating an effective methodology for ground-based observation of vegetation in an urban environment. which utilizes ArcGIS Collector for data collection and iTreeEco for data analysis. This case study was conducted on 10 parcels owned by Seattle Public Utilities (SPU), a public utility operated by the City of Seattle that provides fresh water delivery, solid waste management, as well as drainage and waste water management. The methodology was refined and improved throughout the project, and included three steps 1)map construction and site evaluation with ArcGIS Online, 2)field data collection with ArcGIS Collector, and 3)ecosystem service analysis with iTree Eco. Results from 463 trees indicated that those sites that contained the largest quantities of trees had the lowest tree densities. Forest structure consists of predominantly small trees (60% >6" DBH), with Doulgas-fir being the most common species. Analysis of ecosystem services indicated that mature conifers provided the greatest quantity and breadth of ecological services, and should be protected and maintained for their ecological value. However, a diversity of ecosystem services and the increased resilience to risks such as pests or stress due to climatic change would be achieved through maintaining a diversity of tree species.

Project Context & Relevance

Urbanization and suburban sprawl, combined with human population growth, are global phenomena that have been persistent over the past two centuries, resulting in greatly increased human populations within urban and suburban areas. This trend is expected to proceed at rapid rates in developing countries, particularly within the continents of Africa and Asia (World Bank 2017). Suburban sprawl has been most strongly associated with the form of development in the United States post-World War 1, and has been consistently associated with environmental degradation (Barrington-Leigh and Millard-Ball 2015). Urban areas and suburban areas contribute to environmental degradation through habitat loss and fragmentation (Liu et al 2016), and through the alteration or cessation of ecological processes, such as wetland formation and those processes that connect terrestrial and aquatic environments (USFWS 1990). Furthermore, humans in urban and suburban areas are also sources of and vectors for invasive plants, which colonize natural areas that may otherwise have been unaffected by urbanization and suburban sprawl (Pysek and Richardson 2010). However urbanization in contemporary times is often seen as an opportunity for the densification of human populations, which could potentially reduce the pressure to develop previously undeveloped natural areas. Furthermore, many engineering solutions have been proposed, designed and tested in order to improve ecological functions within urban areas (Seto et al 2010).

These trends all hold true for the metropolitan area of Seattle, Washington. Seattle has been the fastest growing metropolis in the United States since 2010, adding over 100,000 inhabitants in less than a decade, expanding an already large metropolitan population by over 20% (Balk 2018). Seattle is located in the estuary of Puget Sound, a transitionary ecotype between aquatic and terrestrial environments, and critical habitat for the success of many flora and fauna of the region, including the iconic Pacific salmonids of western North America. These salmonids (and many other species that rely on them) all have greatly diminished populations due to the pressures of urbanization and suburban sprawl, and some species have been elevated to the status of federally-listed endangered species. Their populations have been reduced primarily due to urban development in estuarine areas, agricultural land reclamation in freshwater floodplains, and production of resources for human populations, particularly the construction of dams for energy production and water storage(Montgomery 2003). In less developed areas, ecological restoration, or the process of assisting the recovery of an ecosystem, may be a feasible option for the restoration of habitats and ecological processes (SER 2002). However, in urban areas, ecosystem restoration is usually impossible due to the need and desire for the built environment that supports human communities within urban and suburban areas (Martin 2017). Yet despite these limitations, cities can take active roles in managing the 'urban ecosystems' within them, which could include such actions as preserving and increasing green space, preserving and increasing habitat corridors (aquatic and terrestrial) that connect otherwise small and disconnected habitats, and effectively managing vegetation to maximize the provision of ecosystem services. The management of urban vegetation for ecosystem services is one approach the City of Seattle has taken to attempt to reduce environmental degradation associated with urban growth, and to increase the functioning of ecological services provided by vegetation (City of Seattle 2013). Ecological services provided by vegetation include reduction of stormwater runoff flows, sequestration and storage of carbon, and the improvement of air and water quality, as well as wildlife habitat (Seattle Public Utilities 2015). Trees are a component of urban vegetation that provide all of these ecosystem services and more, dynamically throughout the course of their lives. Many U.S. cities, including the City of Seattle, have made numerous efforts to try to understand the ecological services provided by urban tree canopies (Cabaraban et al 1987; Strunk et al 2016). Efforts to quantify the scale urban tree canopies have recently focused on remote sensing technologies, such as aerial photography and LiDAR (Walker et al 2007; Alonzo et al 2015). Ground-based sampling methods have also been used to quantify tree canopies, and while this approach is typically more time consuming, it is typically less costly compared to remote sensing, and can provide a greater degree of detail about urban trees and urban vegetation (Nowak et al 2008). Several researchers have explored the pros and cons of remote canopy surveys compared to ground-based canopy surveys (Fiala et al 2006; Paletto and Tossi 2009; Chen 2017). In 2016, the City of Seattle conducted high resolution LiDAR survey to assess tree canopy cover, which determined that the extent of tree canopy cover in Seattle is 28% of the total municipal area (Seattle’s Urban Forest Team 2017). However, it has also been shown that native tree species may exhibit increased mortality rates in developed areas due to challenges in these environments, and the combined impacts of climate change (Betzen 2018). This case-study sets out to further improve the understanding of Seattle's urban ecosystem through a ground-based survey of vegetation, and analyses of the ecosystem services provided by trees.

Project Background

The positive function and value provided by urban ecosystems is often overlooked or minimized as a result of existing degradation and disconnection. Without a greater understanding of both the presence and value of the urban ecosystem, it is difficult to justify and prioritize improvement or protection of the existing urban ecosystem features. Furthermore, as a public utility, it is critical for Seattle Public Utilities (SPU) to better understand the components of urban ecosystem that exist on the properties that they own and manage. This case study aims to 1) develop a practical approach for observing and mapping vegetation, 2) evaluate the ecological services provided by trees, and 3) highlight opportunities for enhancing the urban ecosystem on SPU property. The Urban Ecosystems group within the Environmental Science and Technology branch of SPU secured funding for and initiated this project. This project is led by Josh Meidav, Senior Environmental Analyst at SPU. This project is part of a larger Vegetation Asset Management Plan within the Environmental Science and Technology (EST) branch, which is responsible for the management of a class of assets within Seattle Public Utilities that includes parks, urban vegetation, culverts, urban creeks, stormwater detention facilities, and other environmental assets. These assets are distinct from physical infrastructure (pipes, outflows, reservoirs, etc.) that are managed by other branches of SPU.

Expected Results

This project did not set out with a specific hypothesis, separating this from a traditional scientific study, however there were some expected outcomes of this study. The primary goal of this project was to create an inventory of vegetation on SPU properties utilizing Geographic Information Systems (GIS), and to analyze the data produced through the creation of that inventory utilizing ArcGIS and iTreeEco (i-Tree Software Suite v6. 2019). We expected to create GIS maps of vegetation, and associated data tables, that would allow for long-term management of that vegetation and the aforementioned analysis. This vegetation inventory includes trees, shrubs, and groundcovers, and includes attributes of that vegetation such as species and observations such as size. The quantitative and qualitative data that was evaluated will be covered in detail in the methods section. The project expected to demonstrate the ecosystem services provided by trees on SPU property in terms of several functions, such as CO_2 sequestered, air quality improvements, and stormwater flow-control. It was expected that the case study would develop and refine an efficient approach to continue to inventory & evaluate SPU vegetation beyond this case study. Spatial analysis of collected data through ArcGIS software, combined with publicly available environmental data, was expected to increase the analytical power of data collected. In summary, the expected results were that this case study would create a methodology for mapping and managing vegetation on SPU properties, and provide an initial sample of the analytical power of the collected vegetation data.

Two additional functions of this methodology that are not closely detailed in this report, are: 1) the documentation of maintenance needs and 2) an analysis of habitat values and connectivity across sites. Although these two functions were not examined closely in this case study, but are worth noting as they are included in the design of map feature types. Researchers documented the condition and maintenance needs of observed vegetation (e.g. invasive species removal, tree pruning, safety concerns) and included maintenance recommendations in the attribute tables associated with vegetation features. Analysis of habitat values could be accomplished through the comparison of the maps produced by the case study with supplemental GIS data layers, such as the endangered species and critical habitats layer created by the US Fish and Wildlife Service, as demonstrated through an example in Appendix 3.

Timeline

In pursuit of the above-mentioned objectives, the project consisted of several phases. The first phase was the initial testing of the methodology design. This phase culminated in the refinement of the methods, although some alterations to the methodology continued to be implemented throughout the entire project duration. Field data collection had to be ceased after leaf drop in Fall of 2018 because deciduous tree canopies could no longer be assessed adequately. Finally, data were analyzed through GIS spatial analysis, and through the iTree eco forestry data modeling software. The following represents the seasonal timeline in which the project segments were carried out:

Summer 2018: Methods Testing and Improvement, Initial Data Collection, Methods Refinement

Fall 2018: Complete data collection, documentation of finalized methods and best practices.

Winter 2019: GIS and iTree analysis and initial findings. Presentation of initial findings.

Spring 2019: Report writing and editing.

Project Study Area Description

Seattle is the largest metropolitan center in the State of Washington, and has sustained rapid population expansion over the last decade. Seattle experiences a maritime Pacific Northwest climate, including approximately 40” of rain per year throughout the municipal boundaries. Winters are cool (temperate) and wet, and summers are warm and dry, and annual, seasonal, and daily average maximum (15.0℃) and minimum (7℃) temperatures are very moderate compared with inland sites east of the Cascade mountains. The City of Seattle is highly developed, with scattered few large natural areas, and most ‘green spaces’ segmented and divided by neighborhoods.

Seattle Public Utilities owns 117 parcels throughout Seattle comprising over 300 acres of land area, and additionally owns over 100,000 acres east of Seattle: 90,000 acres in the Cedar River Municipal Watershed, outside of North Bend, WA, and 12,500 acres outside of Carnation, Washington in the Tolt River Watershed. While all of these real estate parcels are of significance to Seattle Public Utilities, this case study is implementing a methodology that is intended to be used within the urban context. Furthermore, this case study looked only at parcels within the southern half of the Seattle municipal boundary, with Denny street representing the northern boundary of the case study area. In south Seattle, historical and societal biases have resulted in a greater amount of environmental degradation and a reduced amount of service provisions from municipal service providers compared to the north Seattle. While an explanation of the causes and mechanisms of these biases are beyond the scope of this report, this context is the reason for all study sites being located within the southern-half of Seattle. One example of the outcome of these biases is demonstrated through statistics on SPU-owned parcel areas and tree canopy cover, depicted in Table 1. One relevant statistic is that two thirds (67%) of the total land area owned by SPU is in south Seattle, however less than half (40%) of total canopy area is located in that sub-area (Table 1).

Site Descriptions

For this case study a total of 10 project sites were surveyed and mapped. These sites consist of several different land uses, including reservoir parks, commercial facilities, and pump-stations. The sites also vary widely in size, from over 50 acres (Jefferson Park / Beacon Hill Reservoir) to less than 3000 square feet (Norfolk Pump Station 17). In 8 of 10 sites, all vegetation was recorded and mapped according to the project methodology, detailed in the next section of this report. These sites were considered “complete inventory” sites, meaning that every individual tree was measured and mapped. The data from these 8 sites, containing a total of 463 trees and 3.65 acres of tree canopy area, represents the data that was analyzed in order to produce the results presented in this report. Of the remaining two sites, Webster Pond served as initial trial site for the “sample inventory” based methodology, which records data from a number of sample plots within a stand, allowing for extrapolation of data from these sample lots to the larger stand. The methodology developed through this trial sample inventory site will be recorded in this report, however the sample based inventory requires a different model for analysis, and therefore data from these two sites is not included or reflected in the results or discussion of this report. The final site, Norfolk Basin, was initially surveyed as a "complete inventory site," but will require a hybrid complete / sample methodology. For this reason, data collected from that site is not included in the analyses for this report.

Table 1: Breakdown of SPU parcel area and tree canopy within those parcels. South Seattle, the study area, is shown to have a disproportionately small canopy area relative to parcel area.

Location	*Number of Parcels*	*Parcel Area (acres)*	*Canopy Area (acres)*	*Canopy:Parcel Area Ratio*
North Seattle	*48*	*99.1*	*29.2*	*0.29*
South Seattle	*69*	*202.2*	*19.2*	*0.09*
Total	*117*	*301.3*	*48.4*	*0.16*

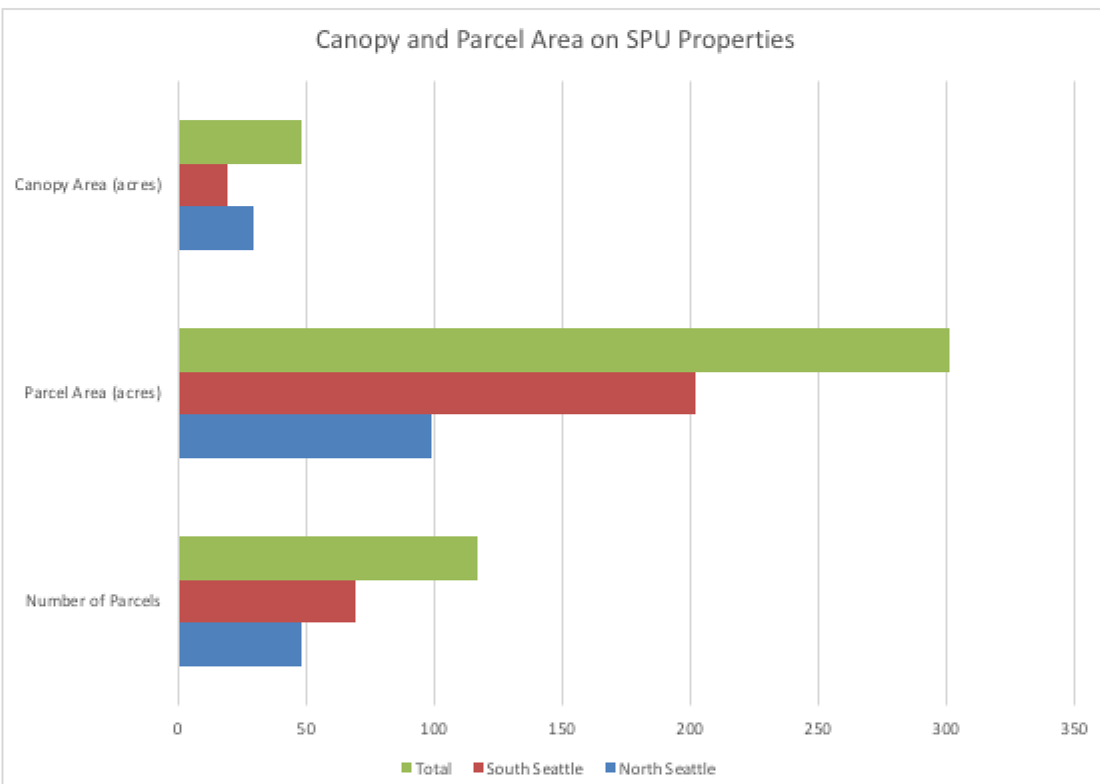


Figure 1: Canopy and parcel area on SPU properties, including totals within the Seattle municipal boundary, and subtotals within the northern and southern segments of Seattle (as divided north and south of Denny Way).

Approach

This case-study demonstrates an approach for the management of vegetation, and synthesizes two technologies, ArcGIS Collector and iTree, in order to create vegetation maps that can be analyzed for the ecosystem services they provide. Specifically, we focused data collection efforts towards collecting physical information on trees and tree canopies, and analyzing the ecosystem services provided by urban trees on SPU property. The study was carried out on ten properties owned and managed by Seattle Public Utilities, from July 2018 through June of 2019. Field data was collected from July 2018 through December of 2018. One of the major goals of this case-study was to develop the methodology that would be used to inventory the urban ecosystem managed by SPU (beyond this project), therefore the methodology was refined throughout the study duration. As each site was surveyed in succession, lessons learned from the vegetation inventory data collection process were integrated into the methodology. In this section, the methodology is explained in its most updated form at the time of writing. Methods that were critical to the evaluation of ecosystem service data, such as decision rules for determining how to measure tree stem diameters (DBH) and canopy widths, were consistent throughout the data collection process, or if necessary, data was collected a second time in order to resolve differences in collection methods. The approach to to this case study involved three major steps. Those were:

1) Map Creation and computer-based preliminary site analyses

An ArcGIS map-file was created with the necessary vegetation feature types (here forward called the “Urban Ecosystems map”). 10 sites were selected for this case study, and those sites were located within the Urban Ecosystems map, and through aerial imaging programs such as

Google Earth. Information relevant to the site vegetation and logistics necessary for surveying the site were recorded. Additionally, observing supplemental data layers in GIS provided important environmental information about each site.

2) Field Data Collection

Each site was visited by field ecologists and all vegetation was mapped utilizing ArcGIS Collector. Utilizing this technology, vegetation units were geographically located within the Urban Ecosystems map as map features, and data were entered directly into the attribute tables related to these map features. Information on species, total area, and management needs was collected for all vegetation units at the site. Additional physical data on trees, including height, stem diameter, and canopy width, was collected for all individual trees on site; the Webster Pond site being an exception, where a sample inventory method was tested.

3) Data quality control and analysis

After data collection was completed, the data were reviewed for quality. Apparent errors in data collection or entry were noted for correction through a subsequent field observation. In some cases, written field notes would be added to the relevant vegetation units. Data on individual trees were then prepared for use with the iTreeEco modeling software. This software produces a number of results related to ecosystem services and pest risks.

Each of these steps will be addressed individually in detail in the following sections. Additionally a step-by-step process for practitioners of this methodology is provided in Appendix 1A and Equipment List in Appendix 1B.

Table 2 - A list and description of the 10 study sites, including land-use categories relevant to SPU management purposes, total site areas, total number of trees at each site, and relative contributions to total study area and total number of trees.

Inventory_Type	Site_Code	Site_Name	Land_Use	Area_sqft	Area_acres	Trees_Quantity	%_Subtotal_Acreage	%_Total_Trees	Difference
Complete Inventory	OCC	Operations Control Center	Commercial	326,830	7.50	46	9%	10%	1%
	PS80	Pumpstation 80	Pumpstation	22,538	0.52	5	1%	1%	0%
	APS	Augusta St. Pumpstation	Pumpstation	35,679	0.82	29	1%	6%	5%
	NPS	Norfolk Pumpstation 17	Pumpstation	3,000	0.07	7	0%	2%	2%
	WSR	West Seattle Reservoir	Reservoir Park	902,128	20.71	59	26%	13%	-13%
	MRT	Myrtle Resevoir and Tanks	Reservoir Park	246,836	5.67	39	7%	8%	1%
	BHR	Beacon Hill Reservoir	Reservoir Park	1,950,181	44.77	253	56%	55%	-1%
	CSP	Charlestown st. Standpipes	Reservoir Park	20,970	0.48	25	1%	5%	4%
	SUBTOTAL - COMPLETE			3,508,162	80.54	463	100%	100%	n/a
Sample Inventory	NFB	Norfolk Basin	Stormwater Pond	244,765	5.62	n/a	55%	n/a	n/a
	WDP	Webster Detention Pond	Stormwater Pond	204,073	4.68	n/a	45%	n/a	n/a
	SUBTOTAL - SAMPLE			448,838	10.30	n/a	100%	n/a	n/a
	TOTAL			3,957,000	90.84	463	100%	100%	n/a

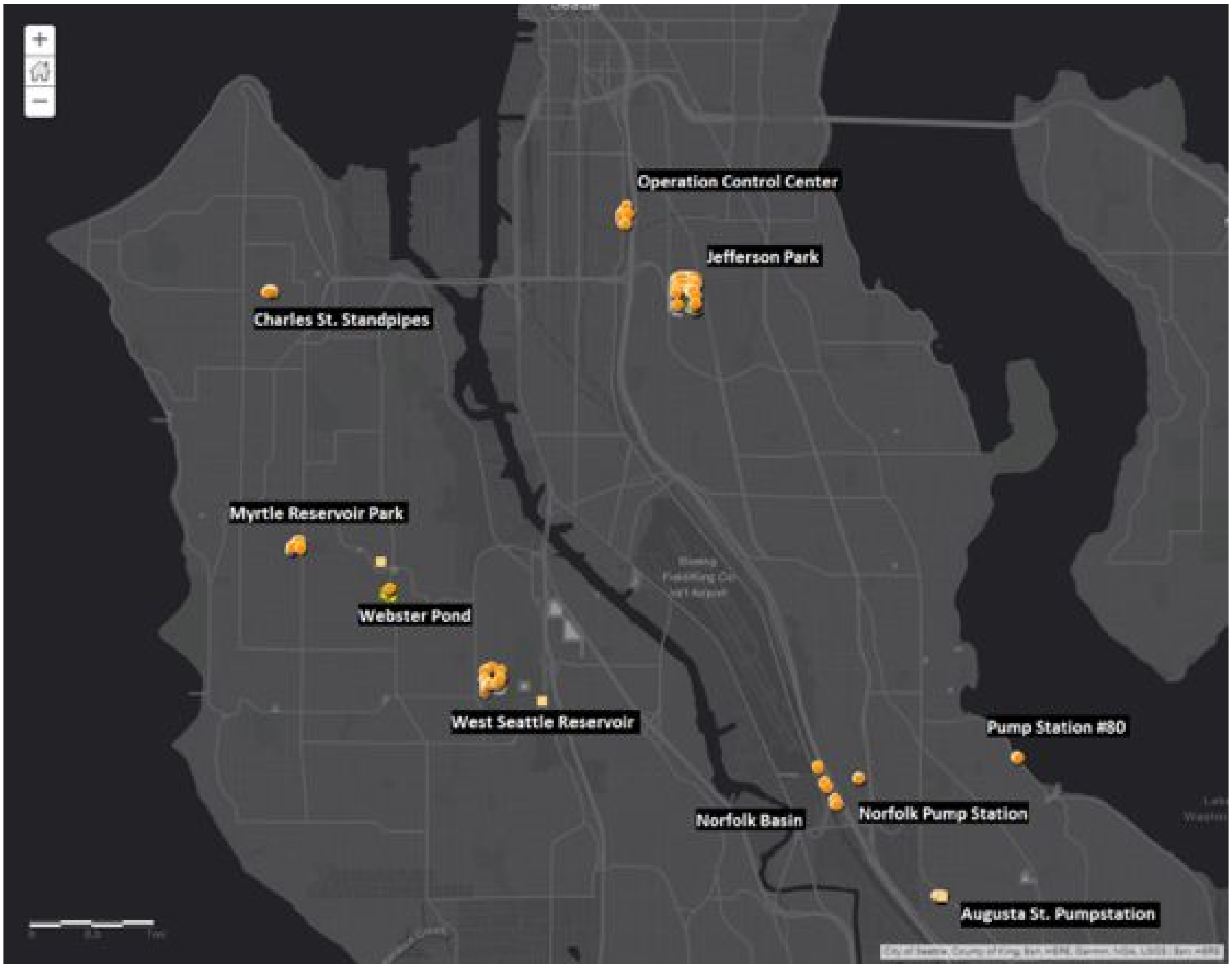


Figure 2 - Map of southern portion of Seattle and individuals site locations. Orange dots represent trees mapped at those locations.

Map Creation & Computer-based Preliminary Site Analysis

The Urban Ecosystems map file was created in ArcGIS Online (ESRI 2019) and project members were assigned editing rights to the file. “**Features”** were designed for characterizing broad groups of vegetation and for project management purposes. The feature types included traditional canopy layer elements such as tree points (individual trees) and tree polygons (stands), shrub polygons, and ground cover polygons, as well as features important for management, such as site location polygons, habitat points, and management points. A full list of the features we utilized and explanations of their purposes can be found at the beginning of the “Individual Site Vegetation Maps” section. After features were designed, we designed the “attributes” of those features.

Attributes included the essential information about a feature that was assumed to be static, for example species, site ID, or the date the feature was created. Each attribute represents a field within a ‘attribute table’ that is associated with a specific feature. For vegetation layers, we included additional nested attribute tables, collectively referred to as **“observations”**. These observations included the essential information about a feature that was assumed to be temporary or indirectly related to the vegetation being mapped. This included physical data such as tree heights and diameters, condition of vegetation, as well as management needs and invasive species; these observations represent temporary information because the trees will presumably grow (or die), and the management needs will be accomplished and/or changed. Organizing the information in this way organized static vs. temporary information, and also allowed for finer-scale organization of data.

Prior to visiting sites it was also important to conduct preliminary site analysis. Sites were viewed within the Urban Ecosystems Map (utilizing aerial photographic imagery of Seattle as basemaps), or within the free mapping programs such as Google Maps. All 10 sites were then located within the Urban Ecosystems map, and “Site Location” polygons were created by tracing the parcel boundaries at each site. Parcel boundary information was obtained from GIS data layers accessible to SPU. Researchers observed the aerial photographic imagery to observe the structure of vegetation at the site, such as the number and location of trees, and the site area. In some cases it was possible to estimate ground-cover layers remotely, particularly mowed grass and turf, therefore ground cover polygons could be created with high accuracy from the computer. No other feature types besides “Ground Cover - Turf” were created at this point in the process, but it was usually easy to locate most trees from the aerial imagery and get a sense for the location and distribution of vegetation at the site.

Preliminary site analysis also benefited from the use of other GIS data layers accessible to SPU that could indicate important environmental features adjacent to or nearby any project site. These supplemental data layers are geographically positioned and function within ArcGIS, which allowed project members to view them within the Urban Ecosystems Map. Examples of data layers that were examined include the location of environmentally critical areas (such as landslides and wetlands), presence of endangered species and critical habitats, and the locations of urban watercourses. An example of the use of a supplemental data layer at an SPU site is provided in Appendix 3. ArcGIS includes vector files such as line, points, and polygons, and raster files such as digital elevation models. This project utilized only vector files for data collection, but raster files from supplemental layers were also used to enhance to analytical value of our data.

Field Data Collection

Field data was collected at each of the 10 sites in no particular order. The field data collected included locations for all management points and vegetation features at a site, as well as all information regarding the attributes and/or observations of features. Data was collected at each site until all vegetation and management features, attributes, and observations were recorded. The time it took to complete data collection at an individual ranged from several hours to several days. The ArcGIS Collector application was utilized on a tablet with a Microsoft operating system in order to collect data in the field. Paper data sheets and notebooks were also utilized to record information in some instances, sometimes serving as a backup to the digital data tables, and also for recording notes about the data collection process or sites. The ArcGIS Collector application displays the Urban Ecosystems map, and allows for the creation of features within the map, as well as subsequent entry of data related to attributes and observations. An example of the interface presented by ArcGIS Collector on a mobile phone can be seen in Figure 3.

Additional tools required for field data collection were a standard 10' Forestry Suppliers brand "DBH-tape" for measuring tree stem diameters (taken at an average of ~4.5 ft above ground surface), a Nikon ForestryPro laser-rangefinder for determining the height of trees, and a 50 ft Lufkin brand measuring tape with engineer scale for measuring canopy widths (engineer scale provides imperial units of measurement within a decimal based scale).

To create features within the map, first a feature type was selected from those designed in the previous "map creation" step, and an example of this can be seen in Figure 3. After selecting a feature type, that feature was located within the Urban Ecosystems map. While using ArcGIS Collector, researchers could see their approximate location within the Urban

Ecosystems map via the GPS internal to the tablet. Map features could be located on the map based on the GPS location of the user (accuracy typically within 2-20’ but sometimes over 100’), or they could be located manually by selecting points or polygon-vertices on the touch-screen display of the tablet. When using GPS location to locate features, points were created at the user’s location, and polygons were created by streaming the location while walking the perimeter of the polygon. Based on the settings we programmed, vertices were created at the user’s location every 5 seconds while streaming. The decision-rule for whether to use manual or GPS-based locating for features was typically based on the data collectors determination regarding the sufficiency of GPS accuracy at that time and location.

When a feature is created and located, ArcGIS Collector prompts the user to enter the necessary information for all attributes of that feature, which were designed in the previous “map creation” step. For vegetation this includes fields such as the species scientific and common names, a tree ID (a unique ID that relates the tree to the site code), and other notes. After a feature is created, and the feature’s attributes are described, observations are then taken when required. Observations were taken for all trees, and for all occurrences of regulated noxious weeds. The ability to make observations and associated tables for shrub and ground-cover type features was designed within the project, but not utilized in this case study; only attributes were recorded for shrubs groundcovers. All features-types were mapped simultaneously as researchers moved throughout the site. If shrub, groundcover, or turf polygons had been created before the site visit, the locations of those polygons were confirmed through field observations.

Shrub and groundcover polygons were composed of any continuous vegetation layers comprised primarily of that vegetation type, not interrupted by deliberate breaks such as pathways. Shrub and groundcover polygons were regularly composed of multiple species, with the species representing over 50% of the polygon area recorded within the attributes. The species comprising the majority of the area was used to determine the precise feature type (i.e. shrub native, shrub invasive). “Native” classifications included all those species native to Western Washington. “Invasive” species classifications included all those species listed as noxious weeds by the King County Noxious Weed program. Ornamental classifications included all other species that were not considered native or invasive. The Groundcover “turf” classification was used for ground-cover vegetation that is maintained via regularly mowing, particularly grass-dominated lawns, but not those areas was grass was present but not maintained by mowing. In cases where species could not be confirmed in the field, the presumed genus or species was recorded, and a note was made within the feature attributes to confirm the species. Vegetative samples and photographs aided species identification outside of the field.

Consistency of the methodology for measuring trees was of utmost important to produce reliable data that ultimately informed the ecosystem service models. Tree “observation” data included DBH, total height, maximum canopy width, canopy health rating, tree health rating, and maintenance needs. DBH was typically determined by measuring the diameter of the main and central stem at 4.5’ above the ground. However, when obstructions prevented measurement at this point, researchers measured the diameter at the nearest point to 4.5’. In cases where multiple stems were present at 4.5’, and no stems were clearly central leaders, then all stems diameters at that height were measured and summed, and the number of stems measured was recorded. All decisions rules for measuring DBH, height, and canopy widths can be found within the field data collection instructions provided in Appendix 1A. A full field equipment list is provided in Appendix 1B. Definitions for canopy health condition can be seen in Appendix 2A.

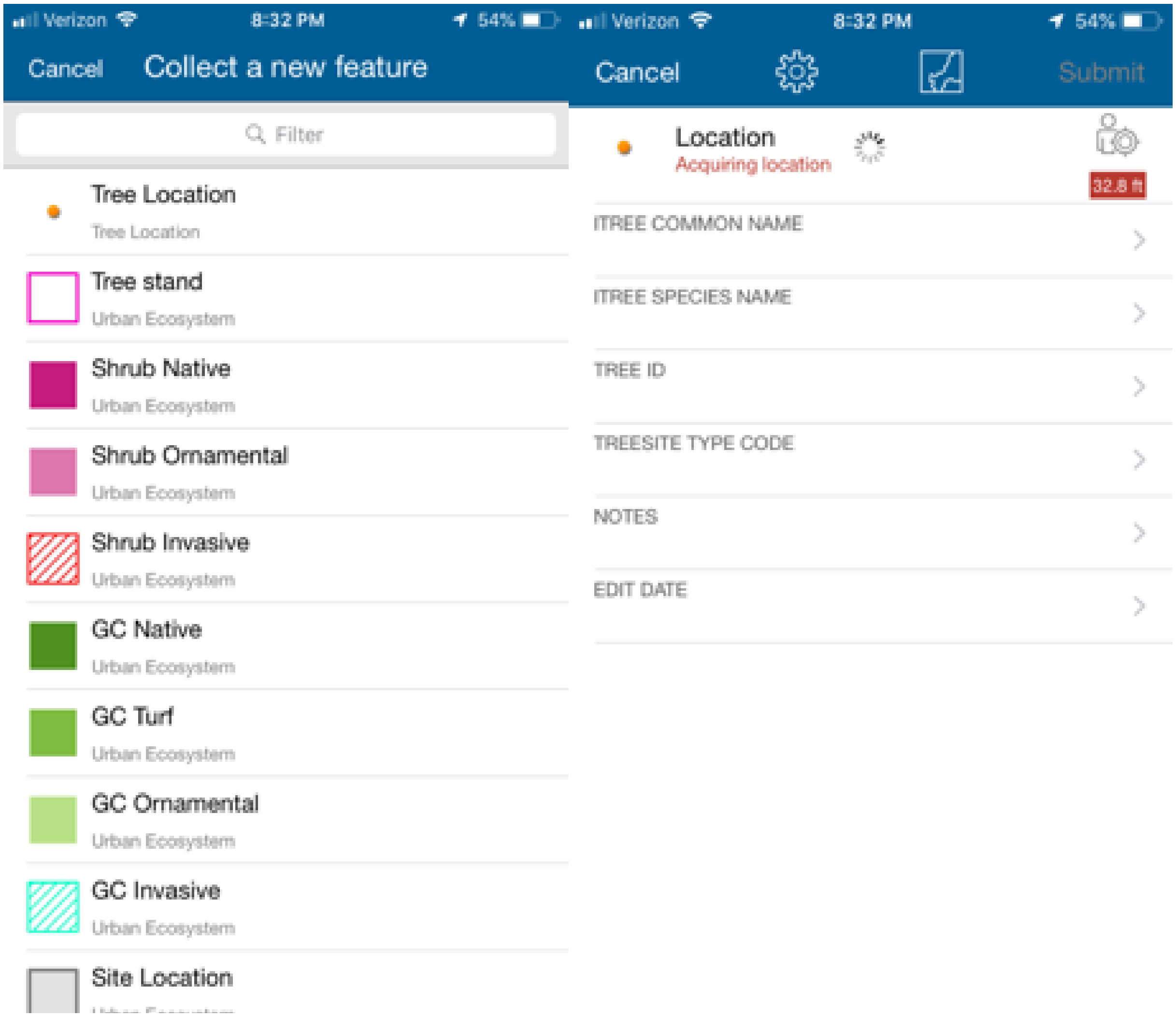


Figure 3: Mobile interface for ArcGIS Collector on a phone. First, a feature type is selected from the list provided. That feature is then located on the map file utilizing either GPS location or selecting a location on the map. Information is then entered into attribute tables associated with that feature through the fields in the subsequent prompts.

Data Quality Control, Data Analysis

After data collection was completed at each site, that data was then reviewed within ArcGIS Online by one of the researchers present for data gathering. Ideally, data review and quality control would occur within 24 hours of data collection, so that researchers would better be able to recollect events and challenges during the data collection process at a particular site. Site maps and associated attribute tables were reviewed for accuracy of feature locations and features attributes and observations. Species identifications that were incomplete or uncertain were also completed at this time utilizing additional reference information, such as the Oregon State University woody-plant identification tool and the Burke Museum online herbarium database. Any missing data fields, and any data entries that appeared inaccurate to the reviewer, were highlighted, and these data were then collected or confirmed through subsequent site visits.

Upon completion of a review of data quality, and completion of all necessary follow-up site visits, data was then prepared for analysis within the iTree Eco modelling software. iTree Eco must be installed with the most up to date version in order to process data; iTree Eco version 6, released in early 2019, was utilized for this study. First, a project file is created within the program and location data and model type is defined. Model type can be either “sample inventory” or “complete inventory”, and thus a “complete inventory” model was selected for this case study, as designed. Project location was selected as Seattle, WA, and the year 2015 was selected as a reference year for weather conditions. This was both the most recent year available for selection, and a year that represented particularly droughty conditions, which is predicted to be an ongoing trend in the Seattle area. The final step in model configuration within i-Tree is to define which data fields have been collected. This case study defined the fields to be considered by the model as follows: species, DBH, tree height, canopy width, and canopy health condition.

The attribute table associated with individual trees in the Urban Ecosystems map was then downloaded through the WebViewer application within ArcGIS Online. Data fields from the attribute table were matched to corresponding fields within the iTree Eco model data tables. Once data tables had been successfully migrated into the iTree Eco format, the software then audited the data for proper formatting. Once a data audit was completed successfully, the model was processed remotely through the submission of project data tables and project definitions. Results were returned via email within approximately 24 hours and were also accessible through the software program itself. In addition to analysis by iTree Eco, attribute tables were analyzed within Microsoft Excel in order to summarize basic information about individual sites, and all sites collectively. This included descriptive results such as site acreage, site land-use, total number of trees at a site, tree density, and relative contribution to total site area, total number of trees, and total canopy area within the case study.

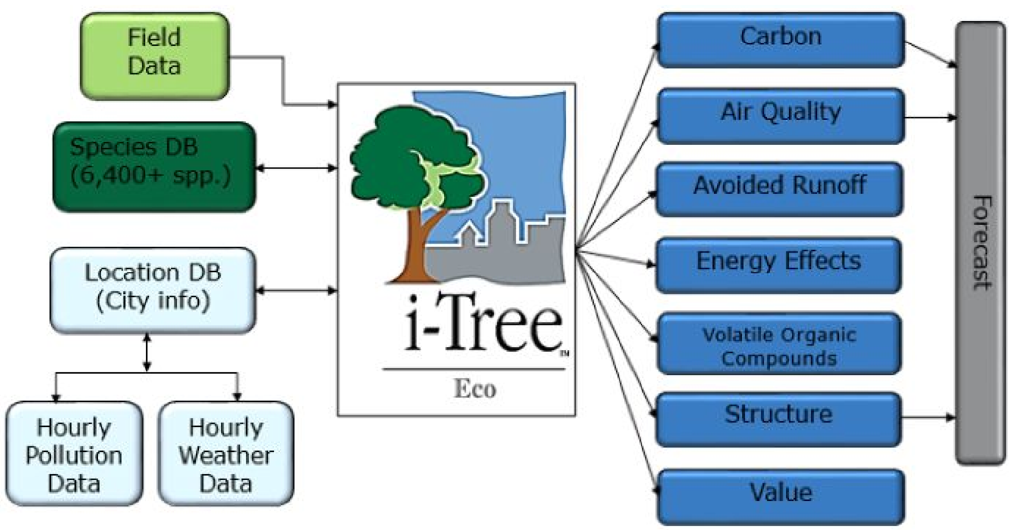


Figure 4: Schematic of iTree Eco model design. Field data measurements of trees in combined with a species database internal to iTree, along with pollution and weather data based on the case study location. Blue boxes list the ecosystem values modeled by iTree Eco.

Methodology Challenges & Limitations

There were several challenges and limitations within this study. First, the season for field data collection was limited. Accurate data regarding tree conditions could not be obtained reliably for deciduous tree species after leaf fall occurred. Therefore, the field data collection occurred from roughly July to October of 2018. Some subsequent field visits were made to data quality assurance, and for recovering some data that was lost during an update of the internal server that hosted the project data. Maintaining consistency in tree evaluation methods across a wide range of native and ornamental species also posed a challenge.

Perhaps the largest limitation of this case study and its conclusions is that project sites selected for data collection during the course of this case study were selected based on logistical practicality, and not statistical explanatory power. Therefore, the data collected throughout this case study can not be extrapolated to explain anything beyond what was surveyed. Now that the methodology for this process has been developed and refined through this case study, we suggest that future efforts by SPU within this framework focus on collecting data across a number of sites that are representative of the range of sites managed by SPU. In particular, this will require the use of sample-inventories such as those demonstrated at the Webster Pond site within this case study. Those sites represent a land-use and vegetation density that is not captured within the data analyses and conclusions of this case study.

Results

Tree Frequency & Tree Density by Land Use

Complete tree inventories were ultimately completed for eight sites (excluding Webster Pond, a sample site, and the Norfolk Basin, a hybrid sample-individual site). A total of 463 individual trees were included in the final tables submitted for analyses within iTree Eco software. Outside of iTree Eco, tree frequency (total number) and tree density (trees per acre) was summarized by three land-use categories, which included "reservoir-parks", "commercial" sites, and "pump-stations". Individual site descriptions and associated land-use category was presented earlier in Table 2, in the Approach section. Approximately 80% of all 463 trees were located within properties categorized as "reservoir parks", while commercial sites and pump-stations each contributed approximately 10% of the total population (Figure 5). However, tree densities within each of these land-use categories was highly divergent (Figure 6). Reservoir-parks were 8% below the average tree density across all sites combined. Commercial sites were planted at approximately the average density, and pump-stations were planted at approximately 7% above the average trees per acre. This results are displayed graphically on the following page.

Combined Forest Structure

iTree Eco estimates a number of factors related to overall forest structure of urban trees. The combined area covered by the tree canopies of all 463 trees was determined to be 3.645 acres, or approximately 14,750 square meters of total canopy area. Canopy diameter were directly measured in this study (as opposed to being modeled based on DBH and species information), therefore the total canopy area figure is considered highly accurate. A total of 54 species were recorded within the population, although 10 species represented roughly 50% the population (Table 5; Figure 7). The three most frequently occurring species (greatest total number across all sites combined) were Douglas-fir (*Pseudotsuga menziesii*), incense cedar (*Calocedrus decurrens*) and swamp white oak (*Quercus bicolor*) (Figure 7). iTree calculates the relative "importance" of tree species by considering the total percentage of a species within the population, summed with the total percentage of canopy area contributed by that species. Therefore, the "importance value" (IV) represents a sum of total percent of population and total percent of canopy area. Through this method of calculation, the top three most important tree species within the study area were Douglas-fir, western red cedar (*Thuja plicata*) and giant sequoia (*Sequoiadendron giganteum*) (Table 3).

The population predominantly consisted of small trees, with nearly 60% (58.7%) of all trees less than 6 in DBH. This size-class distribution was true for the 10 most frequent species (Figure 10), as well as for the population as a whole (Figure 11). Roughly one-quarter of all species were considered native to the State of Washington. When considering continental nativity, roughly 60% of trees were species considered native to North America. Of the remaining 40%, half were considered of Asian nativity, and the other half were native to places other than Asia or North America (Figure 8). All trees combined were determined to have a structural value over $1 million ($1,184,500; Table 4), which represents the estimated cost to purchase effective substitutes (same size and species) for trees if they were to die or be removed today. The three species in the study area with the greatest total structural values were giant sequoia, Douglas-fir, and Japanese zelkova (*Zelkova serrata*) (Figure 9).

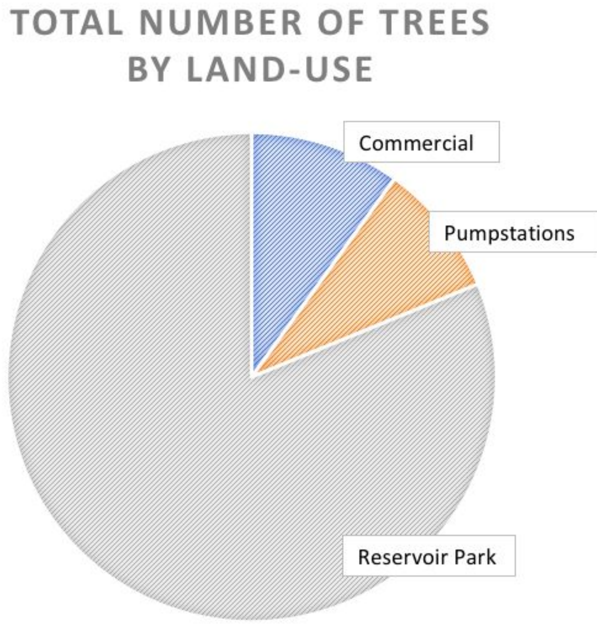


Figure 5: Total number of trees at individual study sites, summed by the land-use category their were assigned. Reservoir parks consisted of most of the land area of sites that were mapped, and contributed over 75% of the total trees included in the data set.

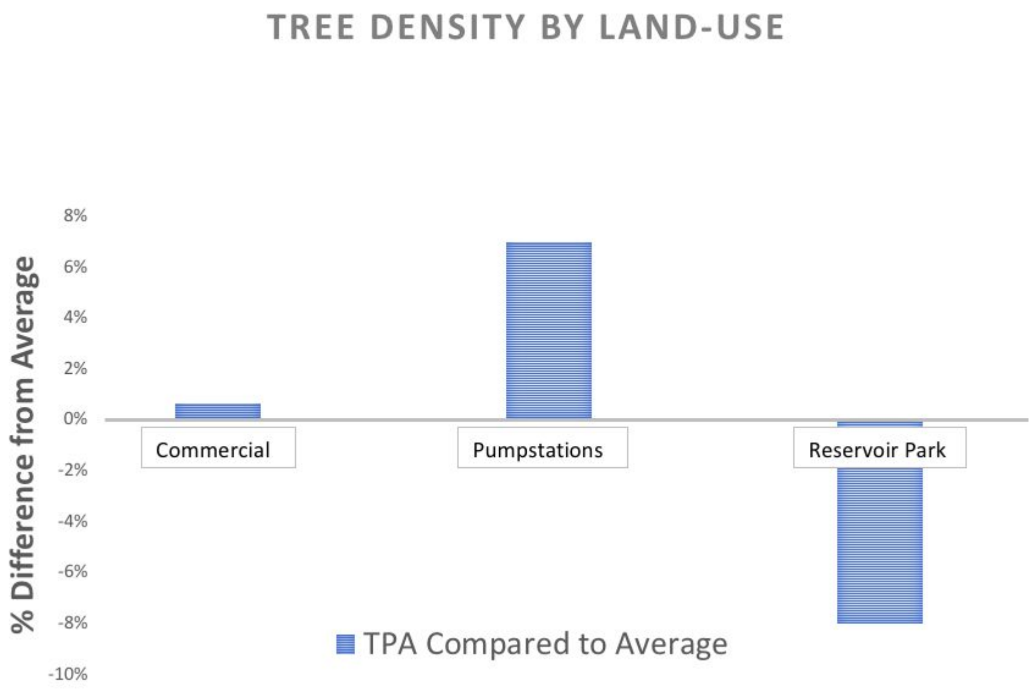


Figure 6: Tree Density by land-use category, compared to the average density across all sites (x-axis). This figure demonstrates that trees at pump-stations are typically planted at above-average densities, and trees at reservoir parks are typically planted at below-average densities.

Forest Structure - Species & Nativity Distribution

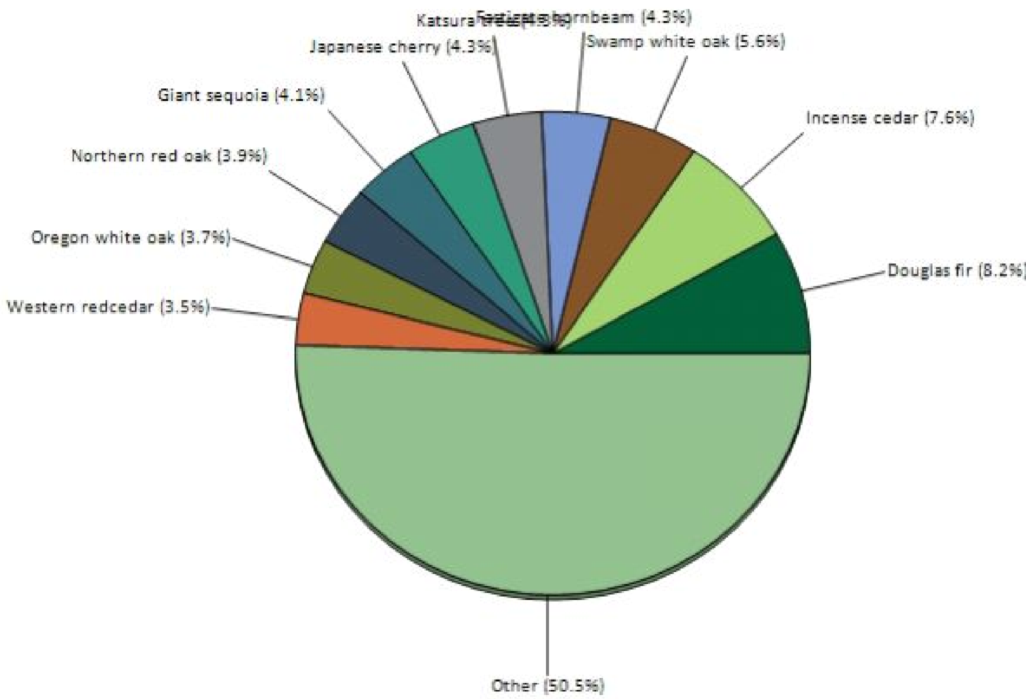


Figure 7: Tree species composition within the study area. This demonstrates that 10 species combined make up roughly 50% of all trees surveyed, and that the three most frequent species combined make up 20% of all trees surveyed. Douglas-fir (*Pseudotsuga menziesii*) and incense cedar (*Calocedrus decurrens*) are the two species that make up the greatest percentage of the overall tree population.

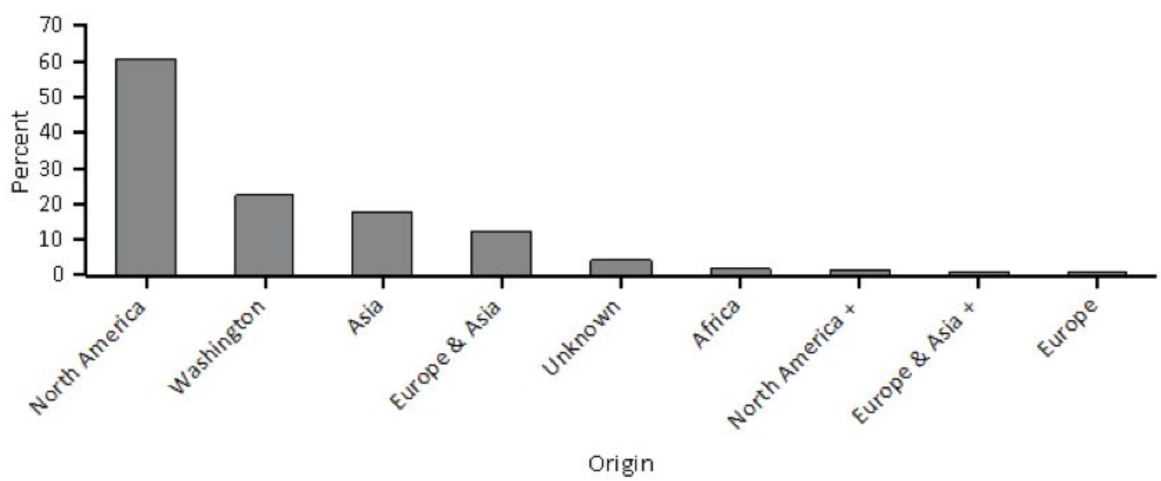


Figure 8: Percent of surveyed live tree population by area of native origin. This chart represents overlapping categories, therefore is not expected to sum to 100%. Furthermore, plant native ranges are not typically constrained by political boundaries, like those native to Europe & Asia. 20% of trees surveyed are considered native to Washington state, and 60% of trees surveyed are considered to be from North American origin (this includes all washington state species). An additional 20% of species are of Asian origin, while the remaining 20% are from other origins.

Table 3 - Representation of ten most frequent species in terms of % of total population and % of total canopy leaf area. Importance Values (IV) as calculated by iTree are the sum of these two values.

Species Name	*Percent Population*	*Percent Leaf Area*	*IV*
Douglas fir	8.2	25.9	34.1
Western redcedar	3.5	10.1	13.6
Giant sequoia	4.1	9.1	13.2
Incense cedar	7.6	2.9	10.4
Atlas cedar	1.7	5.8	7.5
Fastigate hornbeam	4.3	2.7	7.0
Balsam poplar	1.5	4.7	6.2
Swamp white oak	5.6	0.5	6.1
Japanese zelkova	1.7	4.1	5.8
Scotch pine	2.4	3.1	5.4

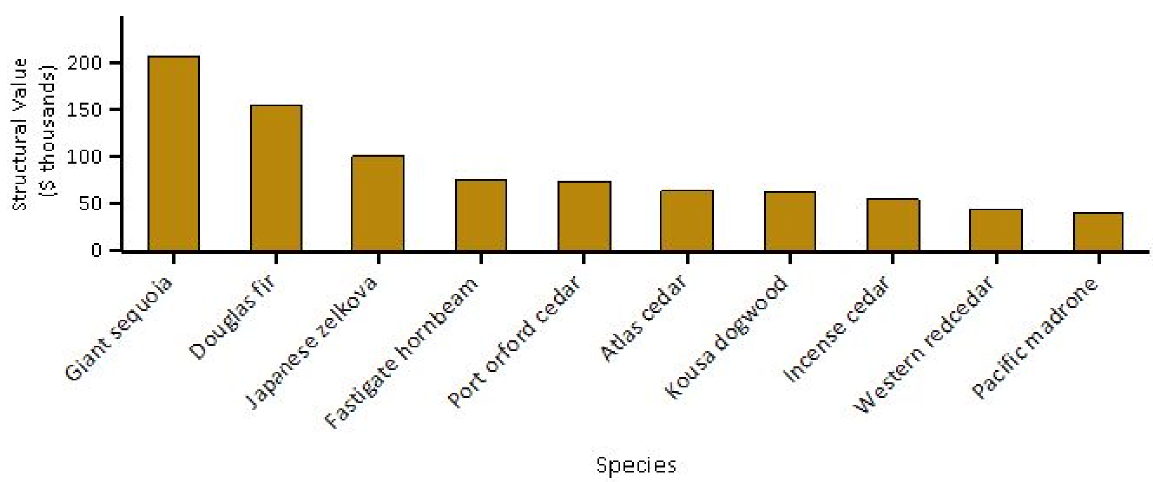


Figure 9 - Tree species with the greatest structural value, which is the value to replace the tree in its current condition if it were to die or be removed.

Urban Forest Structure - Tree Stem Diameter Size Class Distributions

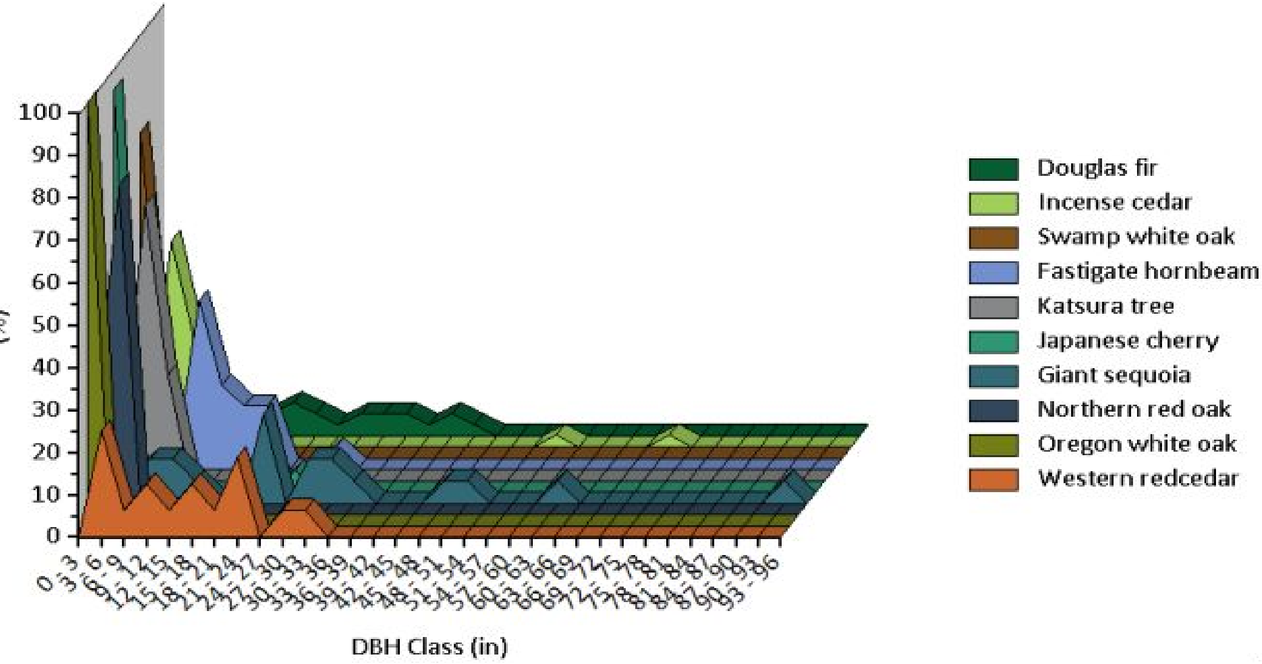


Figure 10: DBH class distribution for the ten most frequently occurring species within the dataset. Each segment of the x-axis represents a 3” range in stem diameters from 0” up to 96”. Most trees are under 2’ in diameter, and the largest tree diameters are represented by the west-coast coniferous species.

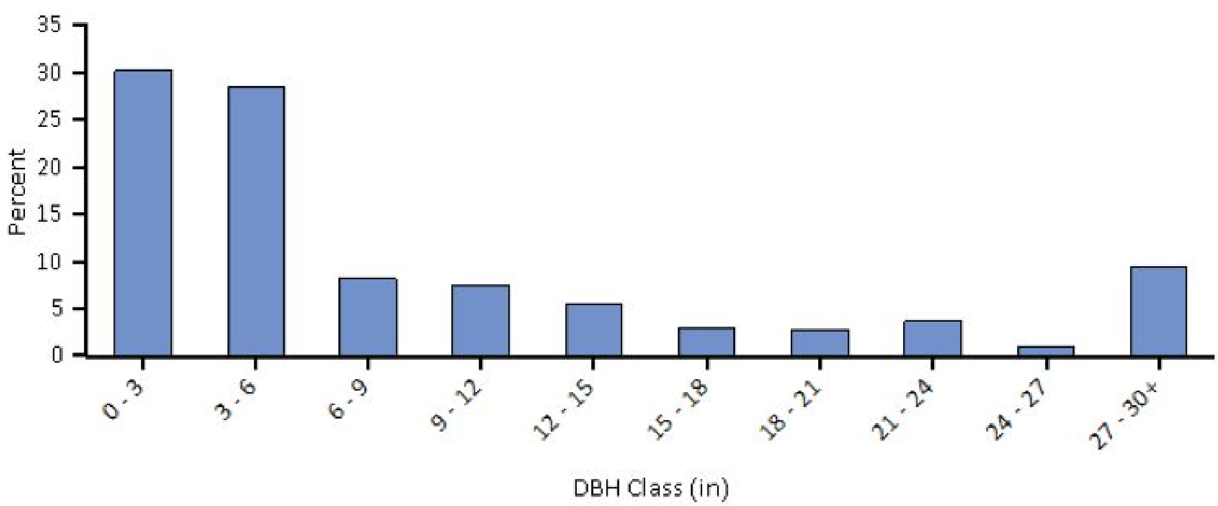


Figure 11: Tree DBH (stem diameters at 4.5’) class distribution for all 463 surveyed trees combined. 60% of all trees were small: below 6” in diameter. All trees with diameters 27” or above are grouped in this figure, showing a weak bimodal distribution between small trees (<6”) and large trees (>27”, with a low frequency of medium-sized trees through the size distribution.

Ecosystem Services

Ecosystem services as modeled by iTree, are reported based on individual species contributions to numerous ecosystem service metrics, as well as a pest-risk evaluation. Table 5 summarizes the benefits provided by all trees within the case study, and Table 6 summarizes those ecosystem services provided by each species present within the population. In order to aid interpretation of ecosystem service results, iTree estimates the dollar values associated with specific quantities of ecosystem services. Carbon storage and carbon sequestration are valued based on the price of $129.73 per ton of carbon. Carbon storage by the tree population is 185 tons, valued at nearly $24,000. Annual carbon sequestration was estimated to be 4.29 tons per year, or an annual value of $556. Runoff flow reductions by the tree population are valued at $0.067 per cubic foot of flow reduction. Runoff flow control was estimated to be 11,135 cubic feet per year, an annual value of $744. Potential runoff flow reductions were based on weather-station reporting of 38.2 inches of total annual precipitation. Pollution removal values are calculated at $1,379.71 per ton carbon monoxide (CO), $6,947.91 per ton Nitrogen Dioxide (NO2), $251.11 per ton sulfur dioxide (SO2), and $369.901.05 per ton of particulate matter at 2.5microns or smaller (PM2.5). Removal of these four pollutants combined was estimated at 188.5 lbs (0.09 tons) per year, valued at $1,833 annually. The tree population was estimated to produce 11.43 tons of oxygen annually.

	N OF TREES	**CARBON STORAGE (tons)($)**	**GROSS CARBON SEQUESTRATIO N (tons/yr) & ($/yr)**	**AVOIDED RUNOFF ($ft^{3/y}$) & ($/yr)**	**POLLUTION REMOVAL (ton/yr)($/yr)**	**STRUCTURAL VALUE ($)**
TOTAL	**463**	**185 $23,997**	**4.29 $556**	**11,135 $744**	**0.09 $1833**	**$1,184,500**

Table 4: Total quantities of ecosystem services provided, and relative values of those services, by all trees in the data set combined. Explanation of calculations to determine benefits below.

Urban Forest Ecosystem Services - Benefit Summary by Species

Table 5 - Summary of ecosystem service provisions, ecosystem service values, and structural values of trees, by individual tree species.

Benefits Summary by Species

Location: Seattle, King, Washington, United States of America
Project: Urban Eco, Series: MEH, Year: 2019
Generated: 2/28/2019

Species	Trees	Carbon Storage		Gross Carbon Sequestration		Avoided Runoff		Pollution Removal		Structural Value
	Number	(ton)	($)	(ton/yr)	($/yr)	(ft^3/yr)	($/yr)	(ton/yr)	($/yr)	($)
White fir	2	1.01	130.55	0.03	3.56	169.21	11.31	0.00	27.86	7,068.46
Grand fir	1	0.24	31.21	0.01	1.33	38.16	2.55	0.00	6.28	1,479.94
Vine maple	5	4.60	596.97	0.14	18.79	63.40	4.24	0.00	10.44	33,785.30
Norway maple	1	0.00	0.35	0.00	0.16	1.54	0.10	0.00	0.25	71.14
Sycamore maple	11	1.06	137.13	0.06	7.67	140.20	9.37	0.00	23.08	8,567.10
serviceberry spp	6	0.15	19.83	0.02	2.65	16.80	1.12	0.00	2.77	2,788.77
Pacific madrone	2	12.30	1,595.21	0.13	16.24	127.17	8.50	0.00	20.94	40,868.96
Paper birch	11	2.12	275.50	0.15	19.58	316.91	21.18	0.00	52.18	16,056.57
European white birch	4	3.87	502.05	0.15	19.05	274.34	18.34	0.00	45.17	20,703.35
European hornbeam	10	0.10	12.94	0.02	2.88	35.43	2.37	0.00	5.83	2,672.95
Fastigate hornbeam	20	9.38	1,217.01	0.41	53.23	301.26	20.14	0.00	49.60	76,330.41
Incense cedar	35	10.51	1,363.47	0.18	23.67	321.23	21.47	0.00	52.89	55,066.06
Atlas cedar	8	9.52	1,235.09	0.15	19.21	647.21	43.26	0.01	106.56	64,164.85
Katsura tree	20	0.64	82.67	0.08	10.67	96.87	6.48	0.00	15.95	11,397.80
Port orford cedar	12	13.41	1,739.80	0.23	29.85	297.58	19.89	0.00	49.00	73,886.24
Kousa dogwood	9	13.42	1,740.98	0.18	23.95	322.07	21.53	0.00	53.03	62,084.56
Cornelian cherry	5	0.02	2.52	0.01	0.92	10.94	0.73	0.00	1.80	472.18
Pacific dogwood	1	0.01	1.59	0.00	0.36	8.43	0.56	0.00	1.39	357.36
Japanese red cedar	2	0.53	69.09	0.02	2.60	45.94	3.07	0.00	7.56	4,434.51
European beech	14	0.19	24.93	0.04	5.70	86.99	5.81	0.00	14.32	3,711.57
White ash	15	0.27	34.60	0.05	6.82	54.50	3.64	0.00	8.97	5,150.27
European ash	1	0.22	29.18	0.01	1.62	52.56	3.51	0.00	8.65	1,601.17
Green ash	2	0.02	2.66	0.00	0.43	5.26	0.35	0.00	0.87	753.56
Ginkgo	4	0.01	0.91	0.00	0.45	4.90	0.33	0.00	0.81	249.92
Tulip tree	10	0.13	16.64	0.03	3.28	56.15	3.75	0.00	9.24	3,845.66
Southern magnolia	1	1.88	243.84	0.05	6.79	24.48	1.64	0.00	4.03	10,706.21
Black tupelo	15	0.22	28.71	0.04	5.67	67.55	4.52	0.00	11.12	6,116.66
Lodgepole pine	9	1.11	143.65	0.05	6.19	145.59	9.73	0.00	23.97	7,513.40
Sweet mountain pine	1	0.03	3.86	0.00	0.37	3.41	0.23	0.00	0.56	522.91
Blue spruce	1	1.31	170.07	0.03	3.80	64.95	4.34	0.00	10.69	4,549.67
Scotch pine	11	1.47	191.11	0.07	9.30	342.01	22.86	0.00	56.31	10,574.94
Balsam poplar	7	13.86	1,798.33	0.24	30.82	523.07	34.97	0.00	86.12	31,955.54
Sweet cherry	2	0.04	4.92	0.01	0.97	28.43	1.90	0.00	4.68	806.84
Bitter cherry	3	0.15	19.95	0.02	2.25	19.03	1.27	0.00	3.13	1,615.71
Japanese cherry	20	2.00	259.28	0.09	11.55	94.79	6.34	0.00	15.61	13,074.75
Higan cherry	4	6.39	829.23	0.18	22.88	152.32	10.18	0.00	25.08	33,405.67
Douglas fir	38	18.40	2,386.94	0.41	53.22	2,881.45	192.61	0.02	474.43	156,244.59
Swamp white oak	26	0.22	27.93	0.05	7.01	52.38	3.50	0.00	8.63	6,325.27
Scarlet oak	1	0.02	2.55	0.00	0.48	11.35	0.76	0.00	1.87	443.59
Oregon white oak	17	0.04	5.78	0.02	2.36	15.02	1.00	0.00	2.47	1,508.86
California white oak	1	3.55	460.74	0.08	11.01	125.83	8.41	0.00	20.72	21,097.66
Pin oak	1	0.02	2.80	0.00	0.50	6.90	0.46	0.00	1.14	463.99
Northern red oak	18	0.29	37.27	0.06	7.60	103.30	6.91	0.00	17.01	6,958.34
Giant sequoia	19	27.76	3,601.83	0.41	53.24	1,017.99	68.05	0.01	167.61	207,451.98
European mountain ash	1	0.77	100.10	0.03	3.83	22.77	1.52	0.00	3.75	4,739.24
Japanese snowbell	10	0.38	49.90	0.05	6.19	124.35	8.31	0.00	20.47	7,119.19
Stewartia	7	0.02	2.06	0.01	0.79	5.36	0.36	0.00	0.88	527.08
Fragrant snowbell	5	0.02	2.63	0.01	0.88	8.32	0.56	0.00	1.37	510.67
English yew	1	0.09	11.91	0.01	0.66	33.41	2.23	0.00	5.50	755.46
Northern white cedar	5	0.01	1.12	0.00	0.39	2.18	0.15	0.00	0.36	231.56
Western redcedar	16	2.86	370.69	0.07	8.95	1,127.12	75.34	0.01	185.58	44,507.57
Littleleaf linden	3	0.04	5.18	0.01	0.82	19.19	1.28	0.00	3.16	1,147.74
Western hemlock	1	0.47	61.22	0.01	1.93	163.33	10.92	0.00	26.89	4,683.03
Japanese zelkova	8	17.81	2,310.94	0.16	21.10	454.41	30.38	0.00	74.82	101,373.66

Urban Forest Ecosystem Services - Annual Pollutant Removal

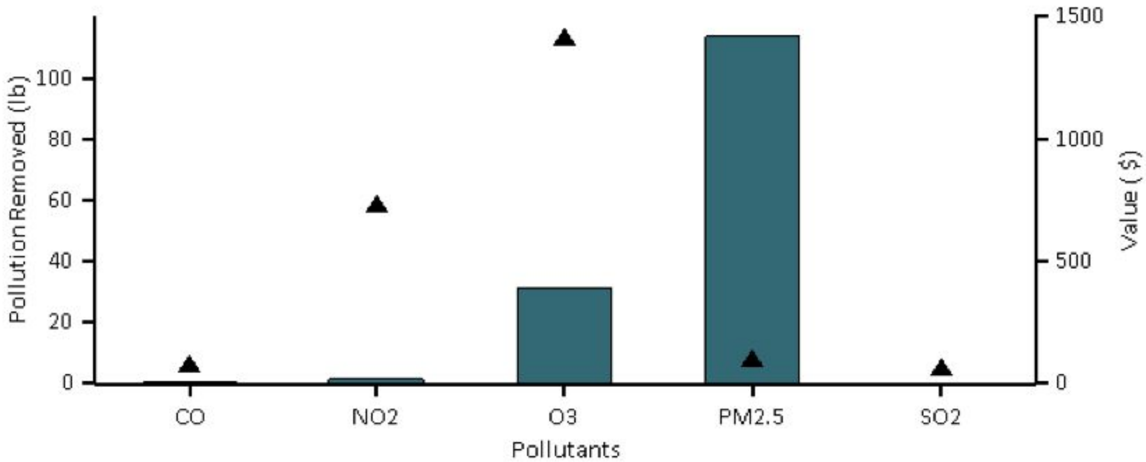


Figure 12: Annual pollution removal (triangles) and dollar values (bars) by surveyed trees. In this chart, we see that removal of pollutants such as Nitrous dioxide and Ozone, have relatively low dollar values compared to the total weight removed. In contrast, removal of small weights of particulate matter is relatively valuable.

Urban Forest Ecosystem Services - Runoff Flow Control Removal

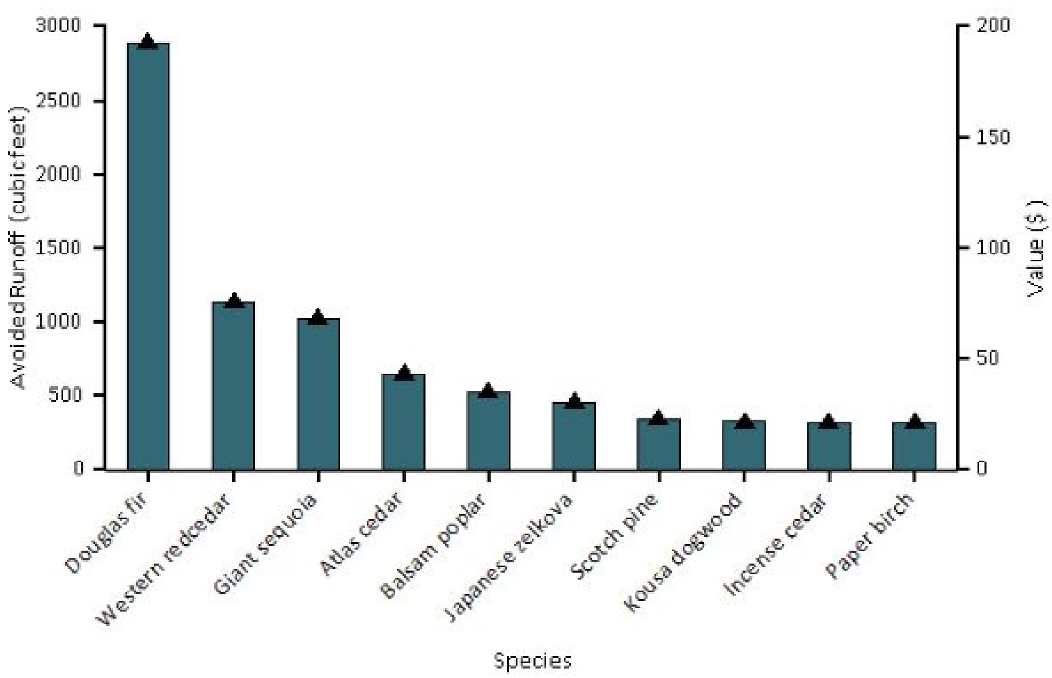


Figure 13: Total cubic feet of surface water runoff managed, and relative values of that service, compared across the ten species that manage the greatest quantity of runoff. This ecosystem service is of particular importance to SPU, as the manager of storm water in Seattle.

Urban Forest Ecosystem Services - Carbon Storage & Sequestration

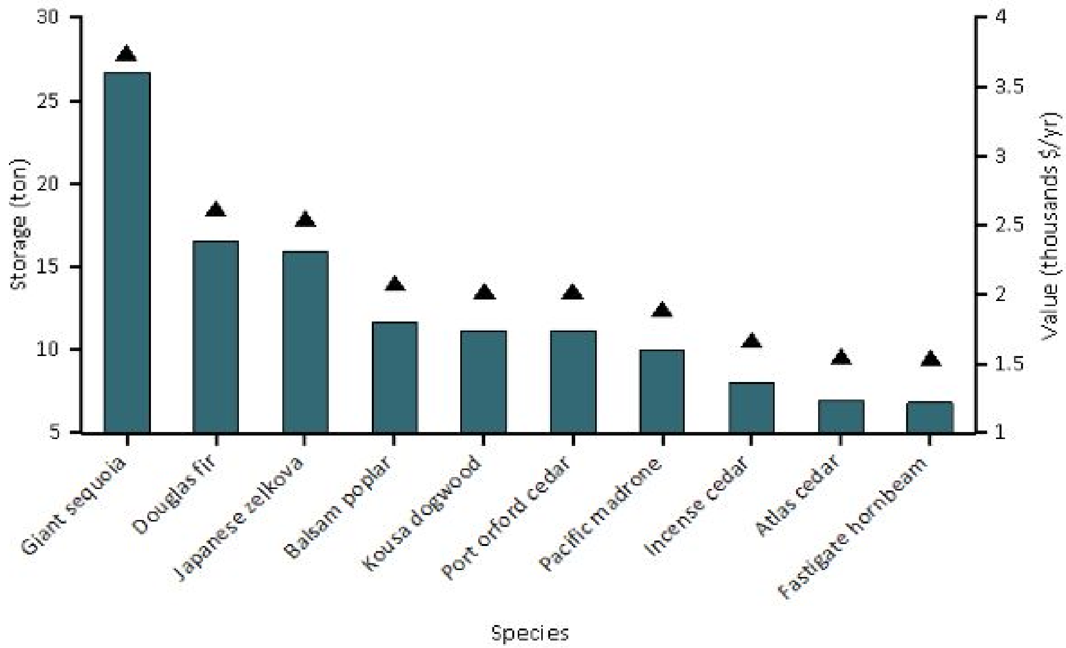


Figure 14: Estimated carbon storage (triangles) and values (bars) for ten tree species surveyed with the greatest carbon storage. Giant sequoias typically create large stems and buttresses which serve as large carbon stores, and those individuals within the study area were mature.

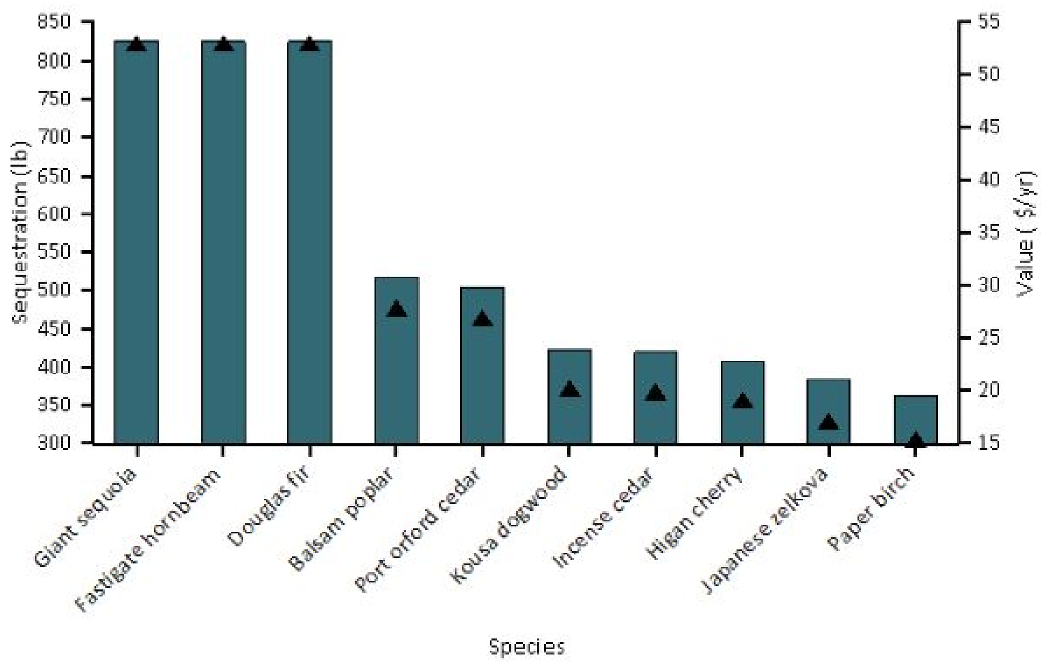


Figure 15: Estimated annual gross carbon sequestration (triangles) and values (bars) for those ten tree species with the greatest rates of carbon sequestration.

Urban Forest Ecosystem Services - Pest Risks to the Urban Tree Population

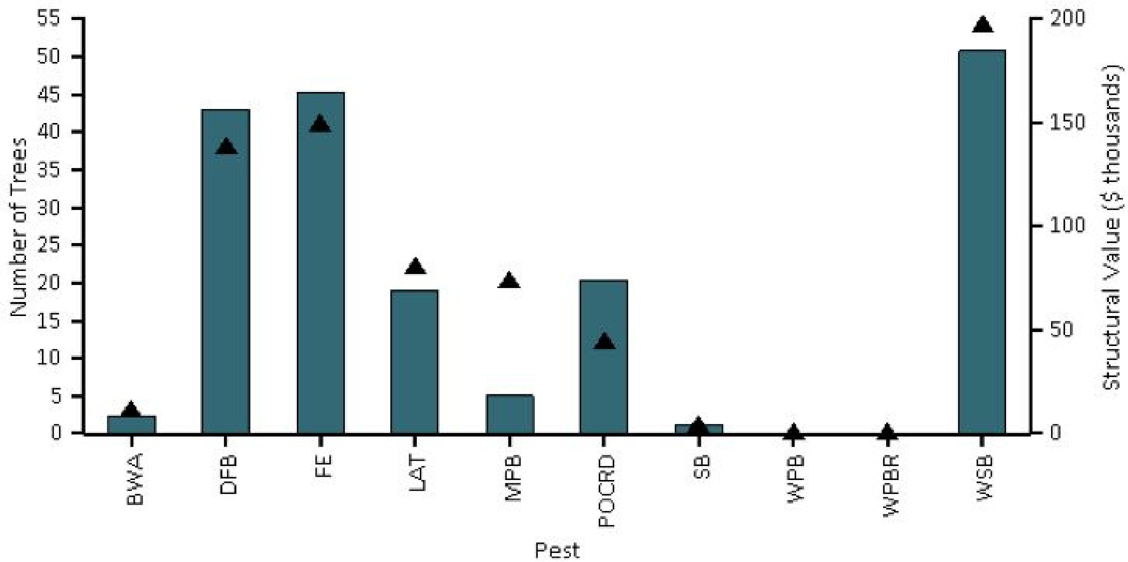


Figure 16: The total number of trees at risk (triangles) and the associated structural values (bars) for those trees at risk, organized by those species of pests known to be located in King County.

Urban Forest Ecosystem Service Results - Potential Annual Air Quality Improvements and Runoff Flow Control

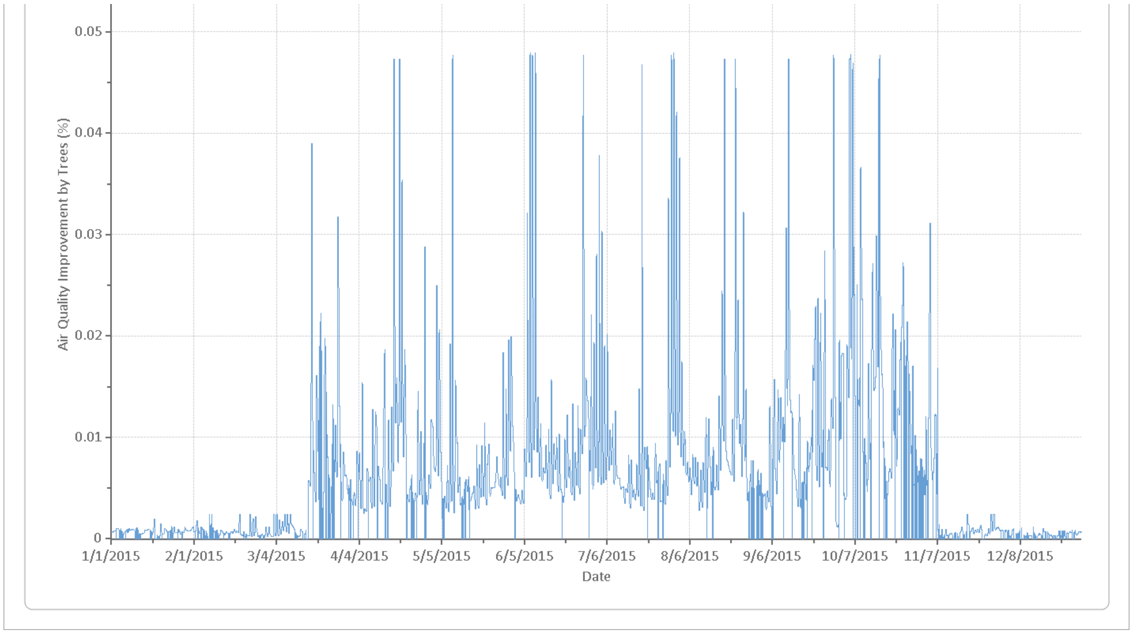


Figure 17: Potential annual air quality improvements by trees within the case study. Air quality improvements are greatly reduced during the winter months when trees are not photosynthesizing ,and deciduous trees have shed their canopies.

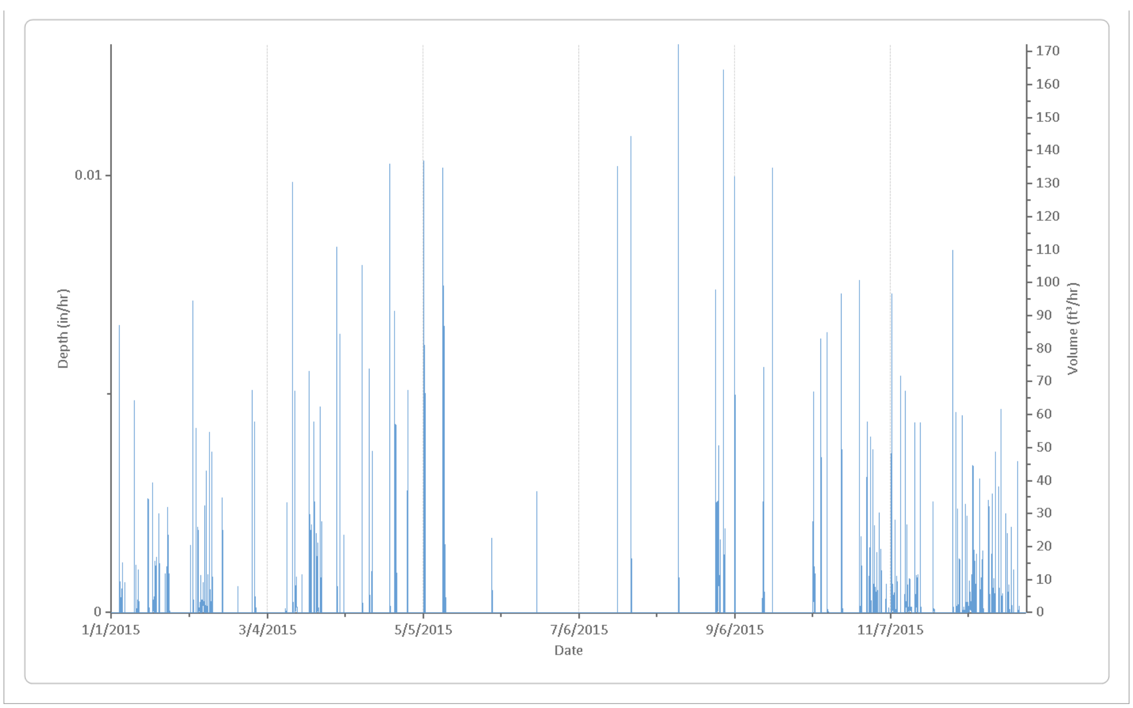


Figure 18: Potential annual avoided runoff, displayed in monthly intervals. Runoff is only produced in a system when there is precipitation beyond what can be absorbed or stored by the vegetation and substrate.

Discussion

The forest structure and ecosystem service results produced by the iTree Eco model, in addition to the descriptive analysis performed in this study, reveal interesting patterns within the urban forest managed by SPU. In this section we will discuss the implications for site and vegetation management of each component of the results.

Land Use Analysis

Reservoir parks represent the vast majority of land area and number of trees within the land uses surveyed within this case study. These sites are also those most regularly accessed by the public, and to some degree represent the most transparent view of ecosystem management by SPU. However, our analysis shows that trees at these sites are planted or maintained at a significantly lower density when compared to all other sites within this study. This suggests that increased planting densities at these sites could result in significant increases in the total number of trees within SPU properties, which would consequently increase the ecosystem services provided by SPU's urban forest.

Forest Structure Analysis

The forest structure analysis results show that the tree population includes a diversity of coniferous and broadleaf tree species, yet only 10 species represent 50% of the population. The significance of this observation is that threats to any of these 10 species, such as an insect pest or change in a climatic condition, could cause significant damage to the overall urban forest. Douglas fir has a particularly outsized role within this population, both as a percent of the population and its contribution to ecosystem services, and thus the tree population could be affected dramatically by large outbreaks of Douglas-fir beetle, or in the case of increased Douglas-fir mortality due to increasing summer drought conditions.

Another significant lesson that can be drawn from the forest structure results is that the population currently consists of a strong majority of small trees, that have relatively small canopies. Protection and maintenance of these trees as they continue to grow and mature will allow for a greatly expanded urban tree canopy, and an increase in associated ecosystem services. Conversely, this observation also draws attention to the relatively small numbers of medium and large sized trees. These infrequent medium-to-large sized trees provide a disproportionately large fraction of the total canopy area, and therefore must be protected in order to sustain the existing ecosystem services.

Ecosystem Service Analysis

The overarching trend of the ecosystem service results is the importance of large trees with large canopies, and the importance of coniferous trees in particular. In terms of carbon storage, coniferous trees make up the top three species in terms of carbon storage, with Giant Sequoia serving a particularly outsized role in this category. This is likely due to the fact that Giant Sequoias produce massive stems and branches, with large buttresses. This is also true for Douglas-fir, although to a lesser extent, which is the species that provides the 2nd greatest quantity of carbon storage. The most significant broad-leaf species in terms of carbon storage is the Japanese Zelkova, which will grow to large sizes with enormous branching trunks. In terms of annual carbon sequestration, we see that perhaps our most significant broad-leaf species within this population is the Fastigiate Hornbeam (*Carpinus betulus*), which produces large canopies and grows to relatively large heights compared to other frequently occurring broad leaved species. Runoff flow control is the ecosystem service that is most relevant to the management responsibilities of SPU. In this measure, the top three species in terms of total volume of potential flow control were all coniferous species. Douglas-fir manages more than twice the volume of runoff compared to any other individual species. This is likely due to the presence of several groves of very large Douglas-fir trees, and the frequency of Douglas-fir within the population. These large evergreen coniferous trees are more effective at runoff control compared to broadleaf trees due to the fact that their canopies are still present during those seasons where the majority of precipitation occurs. The seasonality of potential runoff flow control is demonstrated in Figure 17.

Project Limitations and Challenges

There were some technical difficulties and challenges encountered throughout the project duration. For one, there were occasional technical difficulties in using hardware and software, particularly when using those tools in the field. This included everything from maintaining battery life on tablets, inaccuracy of location streaming, and recording field data digitally, only to have it lost later due to issues on the server where data was stored. Additionally, it was at times challenging to have efficient and effective communication between the ecologist team (Urban Ecosystems team) and the GIS developers (Seattle IT). While these relationships and communication were always professional and ultimately productive, the challenge in conveying the technical concepts and limitations of either field was notable, and should be expected in similar studies. Finally, the complex arrangement of property ownership and management between the City of Seattle’s many agencies occasionally made it difficult to understand parcel ownership and management responsibilities at the sites we surveyed.

Conclusions

Urban ecosystems are increasingly degraded, diminished, and disconnected due to rapid urbanization, suburban sprawl, and increased resource use associated with ever increasing human populations and the implementation of new technologies. These trends are occurring on a global scale and have continued unabated for over a century. Efforts to understand the urban ecosystem and improve ecological function in those systems have occurred in Seattle and elsewhere. Increasingly, the development of urban areas is regarded as a potential avenue for decreasing human impact on the environment, and increasing the function of what remains of urban ecosystems. In Seattle, efforts to document and improve urban tree canopy cover and associated ecosystem services have been an important focus. These services provide benefits that are relevant at both local (storm water runoff control) and global scales (carbon sequestration and reduction of greenhouse gases). Extensive efforts have been made in terms of the use of remote-sensing technologies for mapping tree canopies and urban ecosystems. This study demonstrated an effective methodology for surveying, inventorying, and mapping vegetation within the urban ecosystem, with a particular focus on data collection on urban trees. This mapping methodology also provides the information necessary to analyze the ecosystem services provided by urban trees. This case study demonstrates that the use of several novel technologies, ArcGIS Collector, ArcGIS Online, and iTree Eco, in combination, provide an efficient methodology for surveying vegetation with relatively large analytical power. As important, the results of this study reveal the significance of large coniferous trees for ecosystem services, and increasing the individual numbers and overall cover across the City and SPU assets, especially in historically underserved areas.

Study Area Site Map

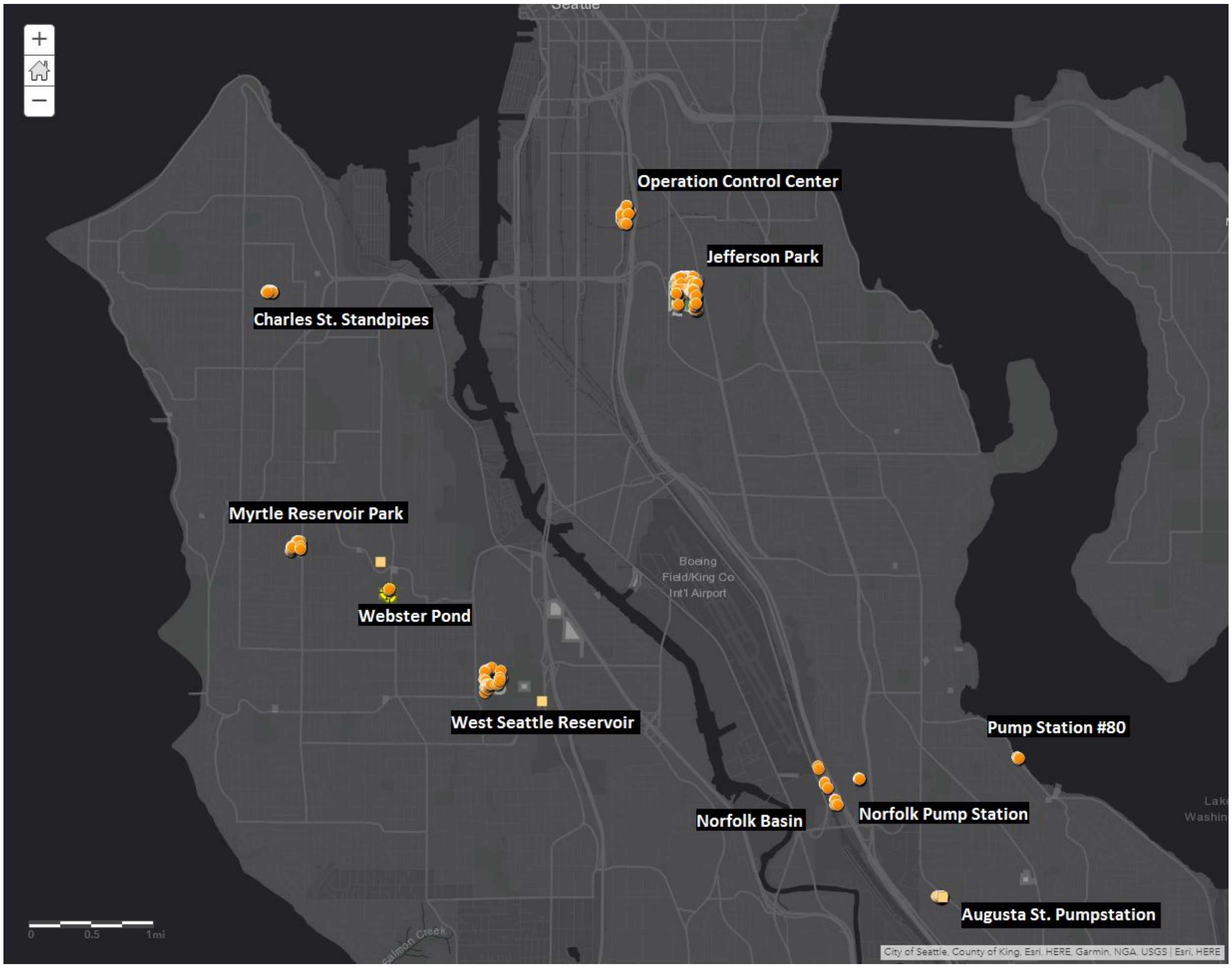
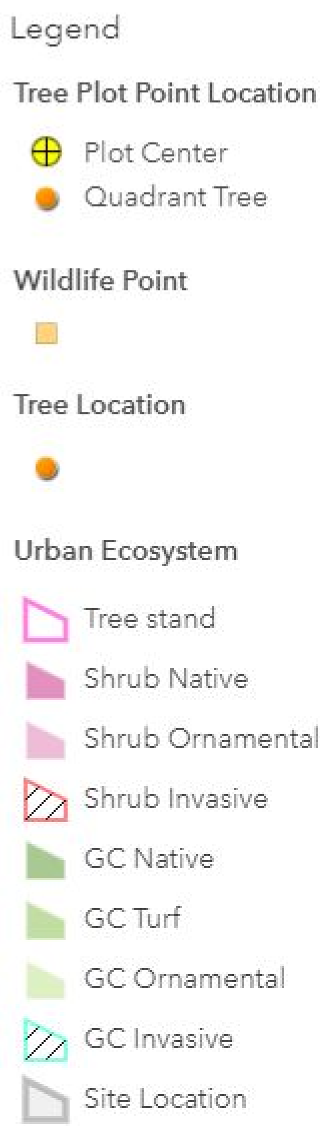


Figure 19: Map of individual sites with labels shown at study area extent

Site Map Table of Contents

Individual Site Vegetation Maps & Legend



Explanation of Legend Item

Plot Center - Point feature defining location of sample plot centroid.
Quadrant Tree - Point feature nearest neighbor in each quadrant relative to Plot Center. Quadrants defined by cardinal direction (NW, NE, SW, SE).

Wildlife Point - Point feature defining location of observed or predicted potential for wildlife habitat, foraging, or location of other ecological importance.

Tree Location - Point feature defining map location of measured tree for complete inventory plots.

Tree Stand - Polygon defining extent of tree stand for plot-based sampling
Shrub Native - Polygon defining extent of shrub vegetation; native species
Shrub Ornamental - Polygon defining extent of shrub vegetation; non-native species, not listed as invasive / noxious weed species.
Shrub Invasive - Polygon defining extent of shrub vegetation; non-native species, State- or County-listed invasive / noxious weed species.
GC Native - Polygon defining extent of ground cover or sub-shrub vegetation, not including turf; native species.
GC Turf - Polygon defining extent of turf-type ground cover, species not important - assumed to be maintained by mowing.
GC Ornamental - Polygon defining extent of ground cover or sub-shrub vegetation, not including turf; non-native species, not listed as invasive.
GC Invasive - Polygon defining extent of ground cover or sub-shrub vegetation, not including turf; listed invasive / noxious weed species.
Site Location - Polygon defining extent of individual site

Figure 20: A legend for all individual site vegetation maps on the following pages. This legend represents all of the map features that were created and utilized for this case study. The order of this legend also represents the map drawing order from top-to-bottom, with Plot Center being drawn on the very top, and Site Locations being drawn as the bottom-most layer.

1: SPU Water Operations Control Center & Parking Lot

Figure 21: Section of Urban Ecosystem Map including the Operations Control Center

Figure 22: Photograph of the Operations Control Center

2: West Seattle Reservoir

Figure 23: Map section of the Urban Ecosystems Map including the West Seattle Reservoir site.

Figure 24: South-facing photograph of West Seattle Reservoir shortly after site development

3: Myrtle Reservoir Park

Figure 25: Map section of the Urban Ecosystems Map including the Myrtle Reservoir Park site.

Figure 26: Photograph of public facing side of Myrtle Reservoir Park

4. Pump Station 80

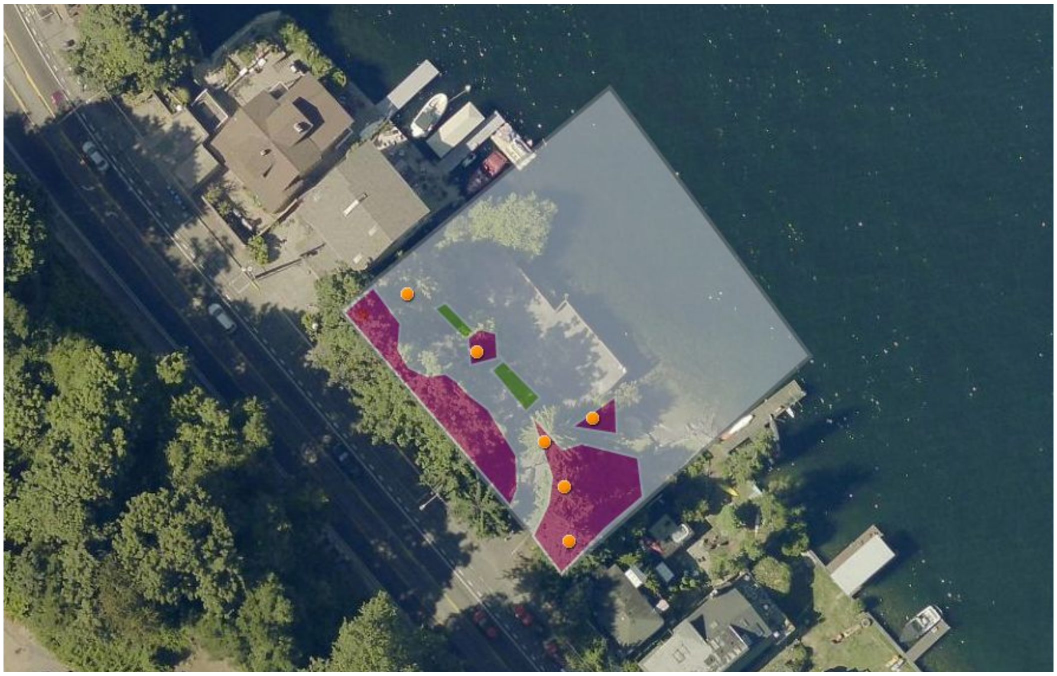


Figure 27: Map section of the Urban Ecosystems Map including the Pump Station 80 site.

Figure 28: Photograph showing the mature native vegetation present at this site, contrasting the asphalt that divides it into road and vegetation.

5. Augusta Street Pump Station

Figure 29: Map section of the Urban Ecosystems Map including the Augusta Street Pump Station.

Figure 30: Photograph of the Augusta Street Pumpstation, including an illegally parked semi that evoked neighborhood ire. A great example of the complications of urban natural areas.

6A. Jefferson Park (Beacon Hill Reservoir)

Figure 31: Map section of the Urban Ecosystems Map including the Beacon Hill Reservoir site. This was the largest site surveyed with the greatest quantity of trees.

6B. Jefferson Park (Beacon Hill Reservoir)

Figure 32: Kids utilizing the splash park at Beacon Hill, highlighting the multiple functions of these sites.

Figure 33: Image of an important stand of Douglas-fir at the northwest corner or Jefferson Park. These trees stand at the edge of a popular view of downtown Seattle, and sometimes considered for removal to improve the view, but the protection of this grove is crucial to retaining ecosystem services at the site.

7. Charlestown Street Standpipes

Figure 34: Map section of the Urban Ecosystems Map including the Charlestown Street Standpipes.

Figure 35: Southwest facing photograph of the manicured vegetation at Charles Street Standpipes.

8. Norfolk Pump Station 17

Figure 36: Map section of the Urban Ecosystems Map including the Norfolk Pump Station #17. This was the smallest site recorded within the case study.

Figure 37: South-facing photograph of the Norfolk Pumpstation, which still included several small and mature trees.

9A. Norfolk Basin

Figure 38: Map section of the Urban Ecosystems Map including the Norfolk basin site. This is a highly urbanized site, between the railroad lines and Interstate-5.

9B. Norfolk Basin

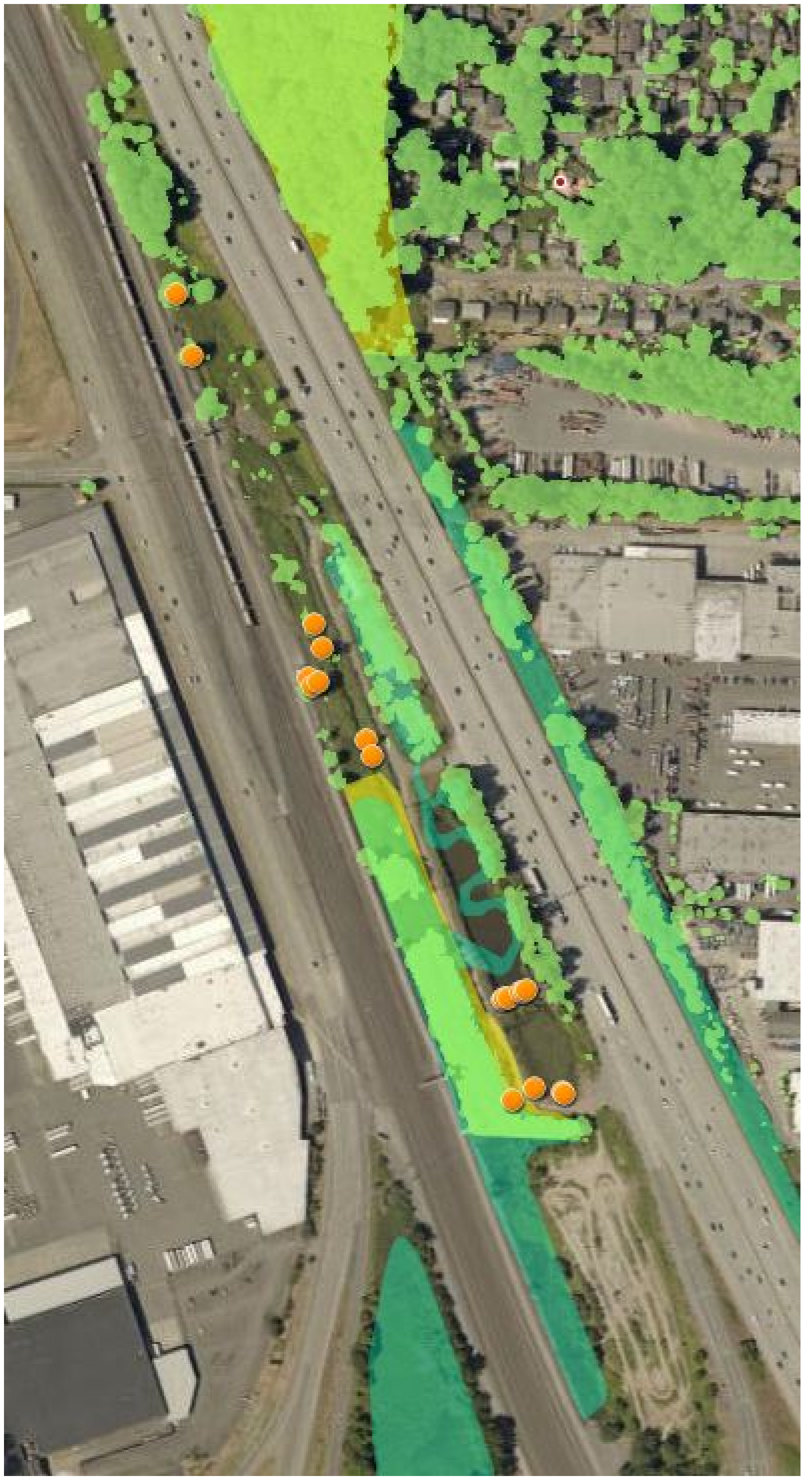


Figure 39: Map section of the Urban Ecosystems Map including the Norfolk basin site including the canopy cover layer (light green) produced by a 2017 LiDAR study across Seattle. This site was initially surveyed within the complete inventory method, but also requires the sample inventory method for full coverage, as can be seen from the canopy cover layer. For this reason, the trees measured at this site were excluded from analysis within this case study.

9C. Norfolk Basin

Figure 40: Photograph of the Norfolk Pumpstation, including water-transport infrastructure.

Figure 41: North-facing photo of the Norfolk Pumpstation, showing the proximity to railroad.

10. Webster Stormwater Detention Pond - Sample Inventory Test Site

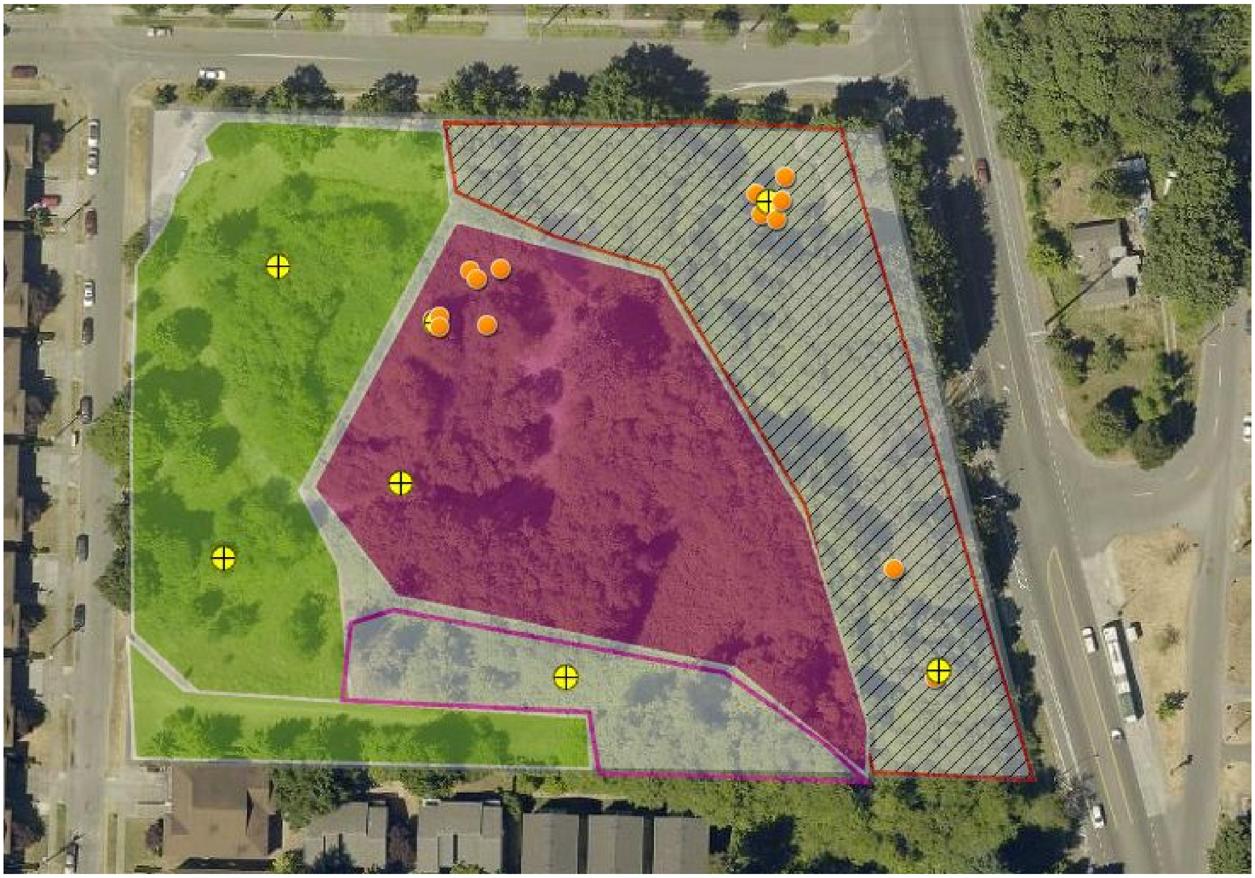


Figure 42: Sample Plots within multiple tree stands at the Webster Stormwater Detention Pond. Plot centers are depicted by cross-hairs, orange dots represent locations of representative trees that were sampled.

Figure 43: Southeast-facing photograph of the Webster Storm Detention Pond.

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Additional Resources

Green Seattle Partnership Forest Inventory Results
https://www.greenseattle.org/forest-inventory-results/

I-Tree Tree Data Collection Protocols & Model Methods
https://www.itreetools.org/resources/archives.php

USFWS Priority Habitat and Endangered Species Program
https://www.fws.gov/endangered/

ISA Tree Risk Assessment
https://wwv.isa-arbor.com/education/resources/BasicTreeRiskAssessmentForm_Print_2017.pdf

Appendices

Appendix Table of Contents

Appendix 1A: Step-by-step Field Methodology Instructions, Decision Rules, Field Safety Essentials

Produced by Scott Davis

Site Boundary Delineation

1. Define area of the target site(s) utilizing “city-owned property” and “parcel” map layers, and/or physical maps of SPU Facilities. Ground truth parcel boundaries while in field and determine if there are any access restrictions on the property. The “city-owned property” layer is not available once working in the field, so it is useful to create site-polygons in the urban-ecosystem map prior to going out into the field.

Tree Points, Shrubs, and Groundcover Polygons

2. Collect data for individual trees, shrubs and groundcovers. A good work flow is detailed below.

3. While moving through the site collecting Tree Point data, map ground cover and shrub polygons when observed.

4. Individual Trees - When GPS accuracy is good, Tree locations can be created by standing next to the tree and creating a tree-location-feature at your current GPS location. Tree-locations can also often be located on the map by cross-referencing GPS location with tree visible in the aerial imagery, and trying to locate the tree-point in the most accurate map location. Larger trees are often easy to locate from aerial imagery.

a. Assign an ID with the following format: “SITEID_##” (i.e. OCC_01). Site ID’s should be sequential.

b. Identify tree species and record scientific and/or common name. Provide as much detail as possible, however identifications to genus are acceptable when species can not be determined with confidence.

c. Measure DBH, Maximum Tree Height, Maximum Crown Width, and record as an “observation” within the individual tree-point feature.

d. Assess both Tree Health and Crown Health, based on the given scale (Dead, Poor, Fair, Good, Excellent), and assign a value to each within the observation.

e. Note maintenance needs & suggested maintenance timeline in observation.

f. Record any other relevant/important information in the notes section.

5. **Shrub Polygons** - When GPS accuracy is good, polygons can be created by “streaming” your location and walking the perimeter of the shrubs. Polygons can also be created manually by cross-referencing GPS location with visible geographic features that can be seen both on the ground and on the aerial imagery, and “drawing” a polygon at the apparent location of the shrub layer. It is important to always ground-truth all polygons that were created only from observing map imagery.

a. If cover is > 50% native, classify as Shrub Native

b. If cover is > 50% nonnative, and the species present are not determined to be listed as state noxious weed lists, classify as Shrub NonNative

c. If cover is > 50% nonnative plants listed on State and County noxious weed lists, classify as Shrub Invasive.

d. Assign an ID with the following format: “SITEID_shrub##” (i.e. OCC_shrub01). Site ID’s should be sequential.

e. Note maintenance needs & suggested maintenance timeline in observation.

f. Record any other relevant/important information in the notes section.

6. **Groundcover Polygons** - When GPS accuracy is good, polygons can be created by “streaming” your location and walking the perimeter of the groundcover. Polygons can also be created by cross-referencing GPS location with visible geographic features that can be seen both on the ground and on the aerial imagery, and drawing a polygon at the apparent location of the shrub layer. This is particularly helpful for areas with large amounts of turf, which typically can be easily seen from aerial imagery and distinguished from other vegetation types. It is important to always ground-truth all polygons that were created only from observing map imagery.

a. If cover is > 50% native, classify as GC Native

b. If cover is > 50% nonnative, and the species present are not determined to be listed as state noxious weed lists, classify as GC NonNative

c. If cover is > 50% nonnative plants listed on State and County noxious weed lists, classify as GC Invasive.

d. If cover is >50% mowed grasses, see step 7 to classify as “turf” instead of “groundcover”

e. Assign an ID with the following format: “SITEID_gc##” (i.e. OCC_gc01). Site IDs within the same feature-type should be sequential.

f. Note maintenance needs & suggested maintenance timeline in observation.

g. Record any other relevant/important information in the notes section.

7. **Turf Polygons** – If the groundcover area is turf (mowed grasses), the feature-type should be record as “turf” as oppose to “groundcover”

a. Assign an ID with the following format: “SITEID_turf##) (i.e. OCC_turf01). Site IDs within the same feature-type should be sequential.

b. Note maintenance needs & suggestion timeline.

8. Photo Points – Take geo-located photos capturing as much area of the site within the frame as possible. Four photos should be taken, each one facing each of the cardinal directions (N,S,E,W).

a. Within the frame of a photo, a laminated sign should be included to designate the direction being observed. If this is not practical, the image should be edited to include text stating the cardinal direction being observed.

b. These photos can be uploaded to a folder where they will be geolocated with the map.

9. **QA/QC** – Quality control of data should occur at office. Review GIS-Online and ensure that all features appear accurately located, and ensure that all tree points and/or plots have associated observations. It is also beneficial to regularly download map attribute tables as back-up of your work.

<u>Tree Stands and Plots</u>

Stand & Plot Design

- Determine appropriate number of plots (0.1 acres) relative to Total Stand Area
- Method for determination? Power Analysis? Factor of Stand Area?

- Distribute plots through a logical distribution across the stand, which captures the stand most accurately. Randomly assign plot center points within these plots and create points in Collector app. The determination and locating of plots and plot-centers may be best completed in the office.

In-Field Process

- When in the field, navigate yourself to the plot center points. Adjust center points as necessary (e.g. a plot center can't be located in open water).
- Once final plot center points are located, mark with a stake or other monument, and obtain high-accuracy GPS coordinates for that center point.
- Mark site notes from center (overall condition, plant community, trash, encampments, other).
- Note azimuth of north-south trending. Using a compass, delineate NW, NE, SW, and SE quadrants from center point.

Map & Measure Plot Trees

- Determine the "nearest neighbor" for each quadrant for each species. This is the individual tree that is closest to the plot-center. Mark trees with hi-vis tape. Record GPS coordinates and/or azimuth.
- Measure and record, for each "nearest neighbor", DBH (.1'), crown width (.5'), height (.5'), and distance to plot center (.1').
- Using the densiometer, determine Relative-Canopy-Cover and Absolute-Canopy-Cover for each quadrant. Record cover estimates for each species individually, as well as combined.
- Calculate average cover for the entire plot (all 4 quadrants averaged), both at the individual species level, as well as the average across all species.
- If any species appear in the canopy cover observations which were not observed in the "nearest neighbor" method, locate the nearest individual of that species in each quadrant in which the species was observed. Measure and record DBH, height, crown diameter, and distance-from-plot center for these trees.

Map & Measure Shrubs and Ground Covers

- Define polygon areas of shrubs: invasive, ornamental, native; enter in associated data for shrub layers. Measure individual trees outside plot as tree points.
- Define area (walk perimeter) of turf/grass as needed, depending on accuracy of previous desktop definition: enter in associated data
- QA/QC any unknown species, and/or locations.
- Take photos looking starting from north and going clockwise: looking south, west, north, east into site when walking perimeter at center of line; Take GPS points of cardinal photopoints.

Decision Rules for Data Collection

1. Trees are only measured if they are 4.5' tall or greater and are at least 1” in DBH. DBH of trees with multiple leaders at 4.5' are measured as the sum of dbh of all stems, and number of stems is noted. If branching horizontally, only measure central leader.

2. Tree Height is a measurement to the live (leafed out) top

3. Crown diameter is the maximum diameter within the crown, including leaf area.

4. Height and crown diameter measurements should be recorded to an accuracy of at least .5'

5. DBH measurements should be recorded to an accuracy of at least .1"

Field Safety Essentials

- Sun protection (sunglasses, lip balm, and sunscreen)
- Bug repellent
- Proper clothing and footwear to deal with harsh terrain or inclement weather. Insulation like gloves, hats, and jacket. Rain gear, waterproof hiking/work boots and gaiters are especially helpful in wet times and places and
- First Aid Supplies
- Utility knife or multi-tools
- Machete as needed
- Food
- Lots of Water

Appendix 1B: Equipment List

Table 6 - Produced by Josh Meidav

Equipment

Item	Quantity	Type of Survey (Point or Plot)	Notes	Inventory (7/30/18)
Field Vest	1/staff	Point and Plot		3
Digital Tablet	1	Point and Plot		1
Lanyard for Digital Tablet	1			Temporary cord; on order
Field Book	1	Point and Plot		1
Pens, Pencils, Ruler	3 each, 1 ruler	Point and Plot		in clipboard
Clipboard with Maps, Data Sheets, and Site Locations, and Sampling Protocol	1	Point and Plot		1
Cell Phone/Camera	1	Point and Plot		1
Laminated Cardinal Directions for Photo-points	4	Point and Plot		4
GPS	1	Point and Plot		1
Extra Batteries for GPS	4	Point and Plot		8
Laser Ranger Finder	1	Point and Plot		1
Extra battery for Laser Range Finder	1	Point and Plot		2
Clinometer	1	Point and Plot		1
Indicator Range for Tree Condition and Crown Health Pamphlet	3	Point and Plot		2
DBH Tapes	2	Point and Plot		2
Compass	1	Point and Plot		1
Plants of the Pacific Northwest	1	Point and Plot		1
Wild Plants of Seattle by Arthur Jacobson	1	Point and Plot		1
Stakes: plastic and flagging	5	Point and Plot		5 + 5
Reel Tapes	2	Plot		1
Ziplock Bags	30	Point and Plot		on hand
First Aid Kit	1	Point and Plot		1

Appendix 2A: Health & Maintenance Data Organization

Tables Produced by Scott Davis

Table 7 - "Canopy Health Condition"

ID	Description	Condition %	Report Category
1	95-100%	100	Excellent
2	75-95%	90	Good
3	50-75%	65	Fair
4	5-50%	50	Poor
5	0-5%	0	Dead

Table 8 - "Maintenance Recommended"

ID	Description
1	None
2	Small tree (routine)
3	Small tree (immediate)
4	Large tree (routine)
5	Large tree (immediate)
6	Critical concern (public safety)
7	

Table 9 - "Maintenance Task"

ID	Description
1	None
2	Stake/train
3	Crown clearing
4	Crown raising
5	Crown reduction/thinning
6	Remove
7	Treat pests/disease

Appendix 3: Preliminary Desktop Analysis - Examples

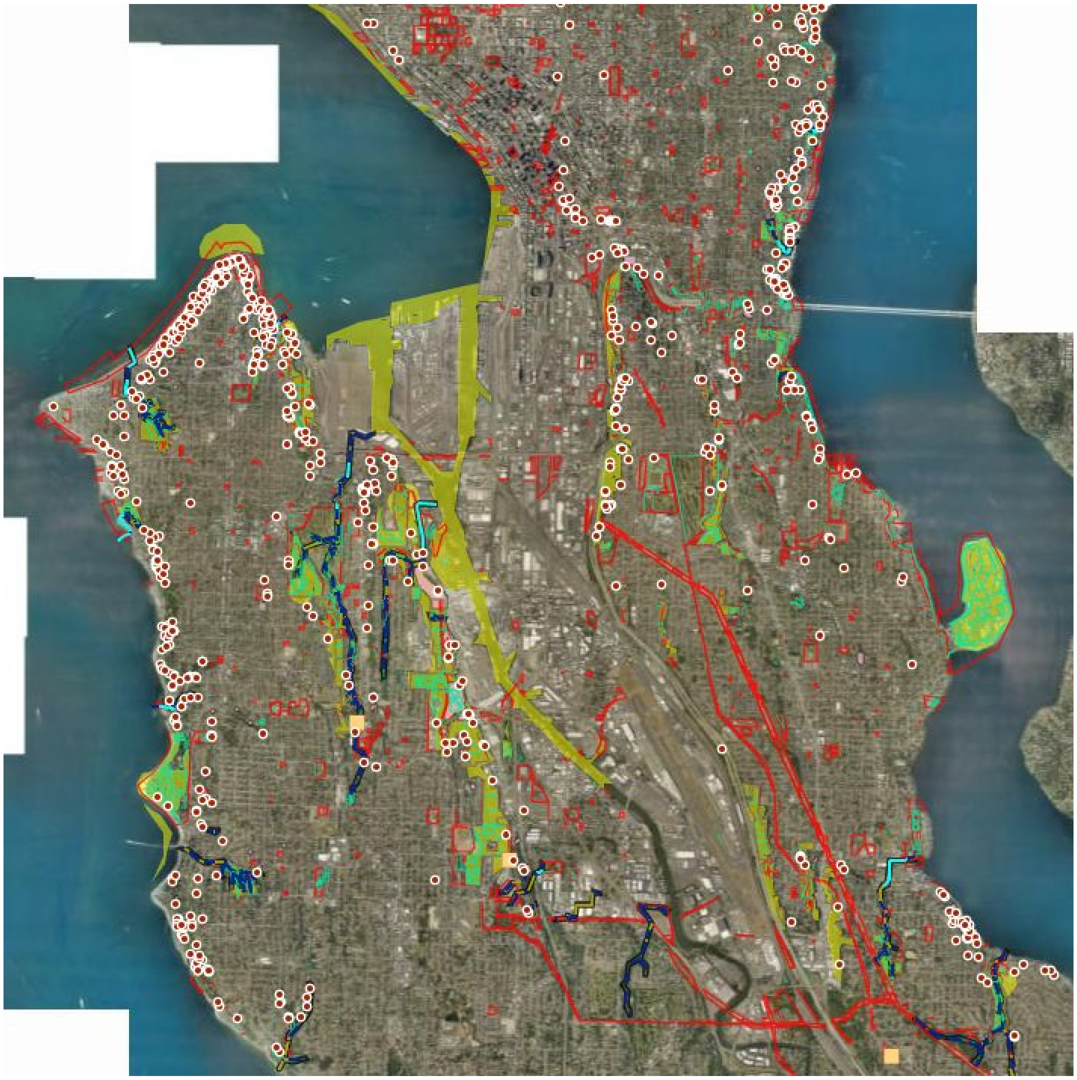
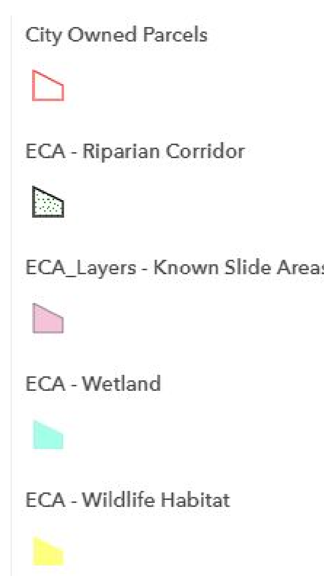


Figure 44: An example of several supplemental data layers that can be utilized to access relevant legal, topographical, or environmental information across an entire study area, or at an individual study site. This analysis informs field data collection and enhances the power of data collected within an individual case study. This example shows city-owned parcel boundaries, environmentally critical areas (including wetlands and wildlife habitats) as well as known landslide locations. The legend is depicted to the right.



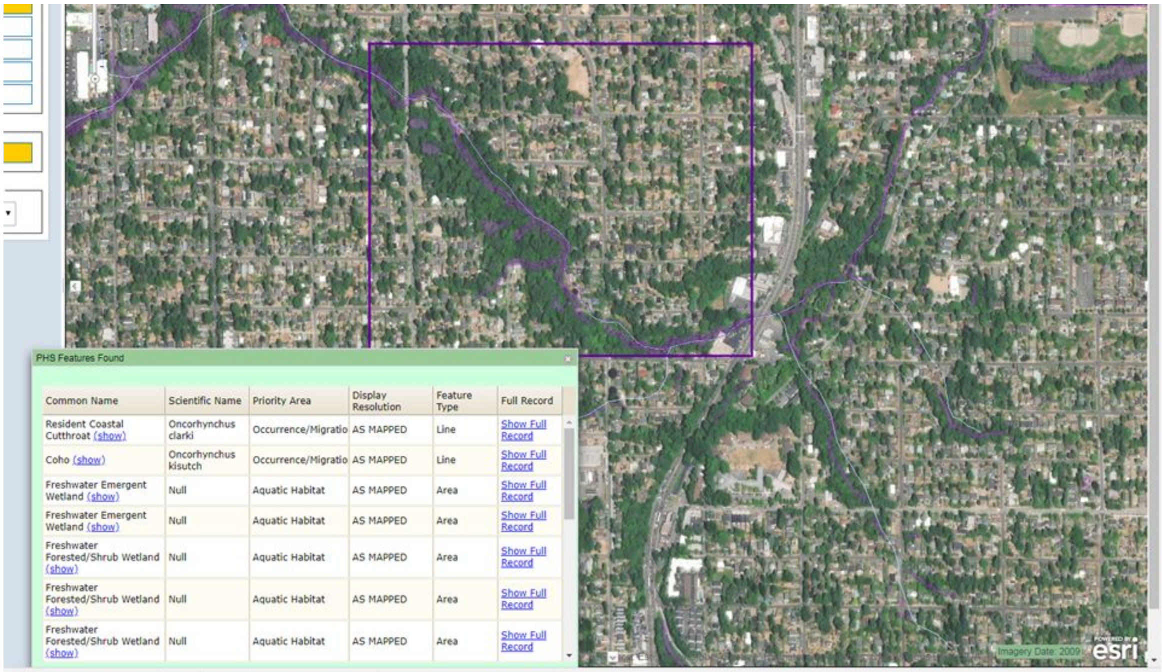


Figure 45: Example of Critical Habitat Area & Endangered Species data layers being utilized for the Thornton Creek watershed, an urban creek system managed by Seattle Public Utilities. The data layer, provided by the US Fish and Wildlife Service and available to the public for a small fee, indicates that two endangered salmonid species, and two critical habitat types, are located within the area-of-interest depicted by the purple rectangle.

1	7972603535	902,128	9000 8th Ave S			point	West Seatt West Seatt SW	lots of turf, few trees at borders, planted
2	3124049028	140,000	9001 3rd Ave SW			plot	SW Trentoı West Seatt SW	Lots of trees and turf
3	2924049099/9006/9104	368,862	130 S Kenyon St			point	South Tran Industrial C SW	Landscaping trees and turf: one area of dense trees
3	7328400005/1175	454,928	130 S Kenyon St			point	South Tran Industrial C SW	Landscaping trees and turf: one area of dense trees
4	7327905700/5710	6,000	698 S Riverside Dr			point	7th Ave S P Industrial C SW	few trees, mostly bare + driveway
5	2924049110	179,082	7207 E Marginal Way	47.537353	-122.318421	Point	Slip 4 - Duv Industrial C SE	shrubbery

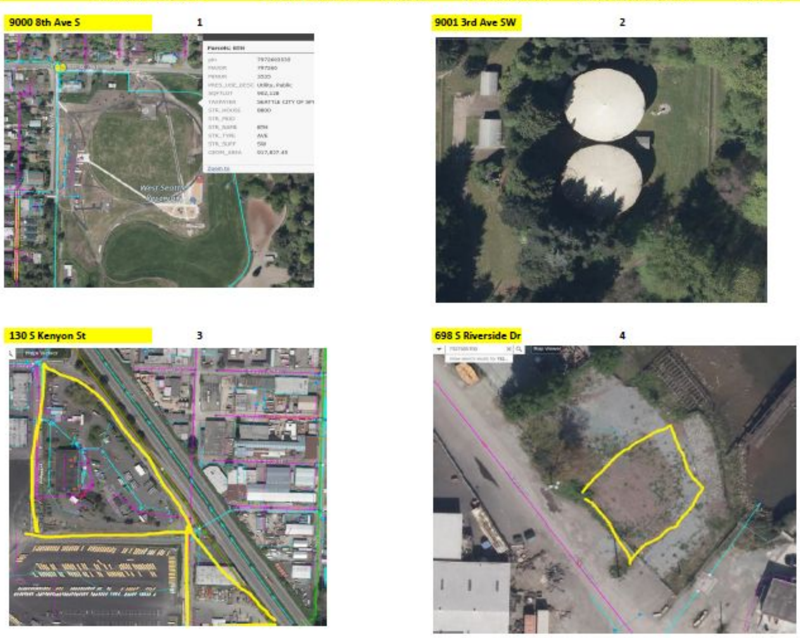


Figure 46: Example of preliminary site analysis: data table with important notes regarding site. Map screenshots of site locations including markups noting important features or boundaries.

Appendix 4: Additional Function of Methodology

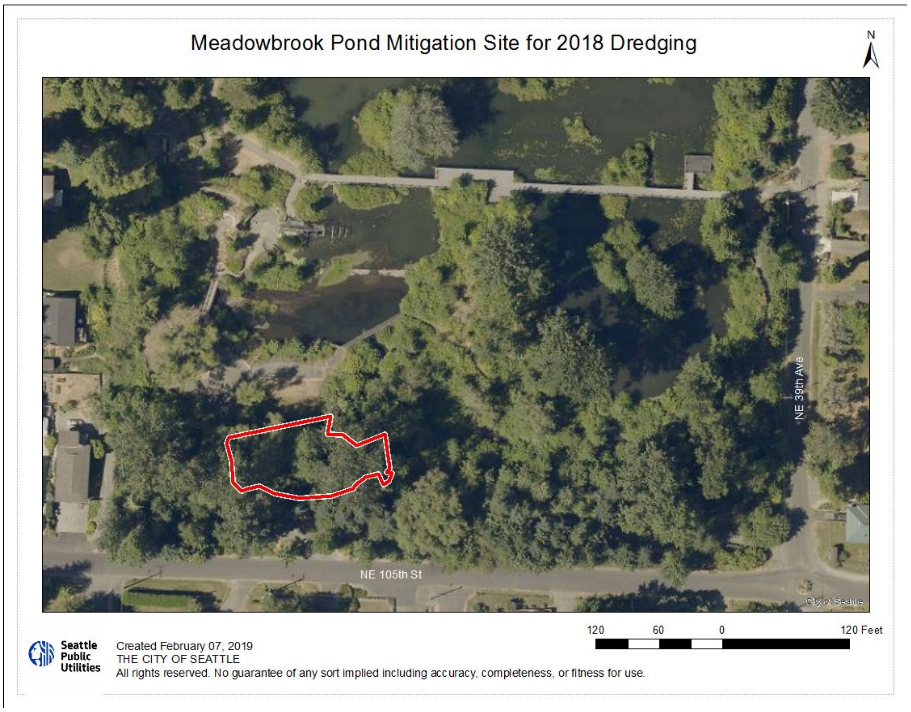


Figure 47: Example of mitigation site mapping utilizing collector and location streaming

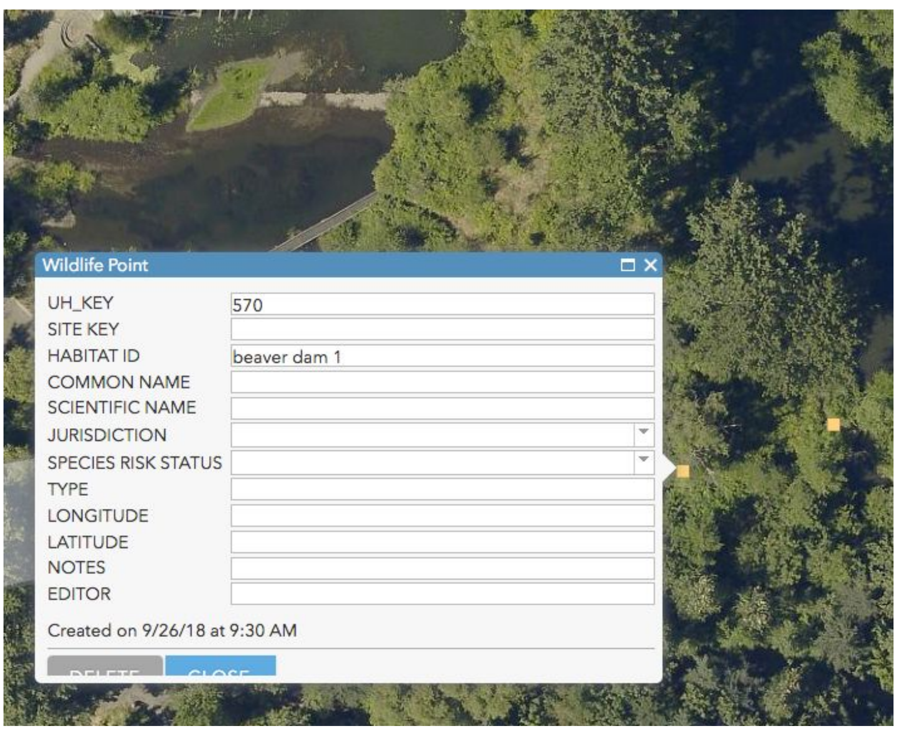


Figure 48: Example of Wildlife Point mapping, in this example multiple beaver dams at a project site are located within the Urban Ecosystems map

Appendix 5: Sample Plot Methodology

Table 10: Example of Plot Status Definitions for defining plot-based sampling

Plot Status Definitions

1. **Forested** = >25% tree cover
2. **Natural** = <25% tree cover + native shrub or groundcover
3. **Sparse** = <25% tree cover + no shrub or ground cover, bare dirt
4. **Landscaped** = <25% tree cover + non-native shrub or ground cover
5. **Hardscaped** = <25% tree cover + concrete or gravel surface
6. **Invaded** = significant presence of invasive trees, shrub, or groundcover
7. **Restored** = restored within last 2 years. Monitoring + maintenance req'd
8. **Other** = any other designation

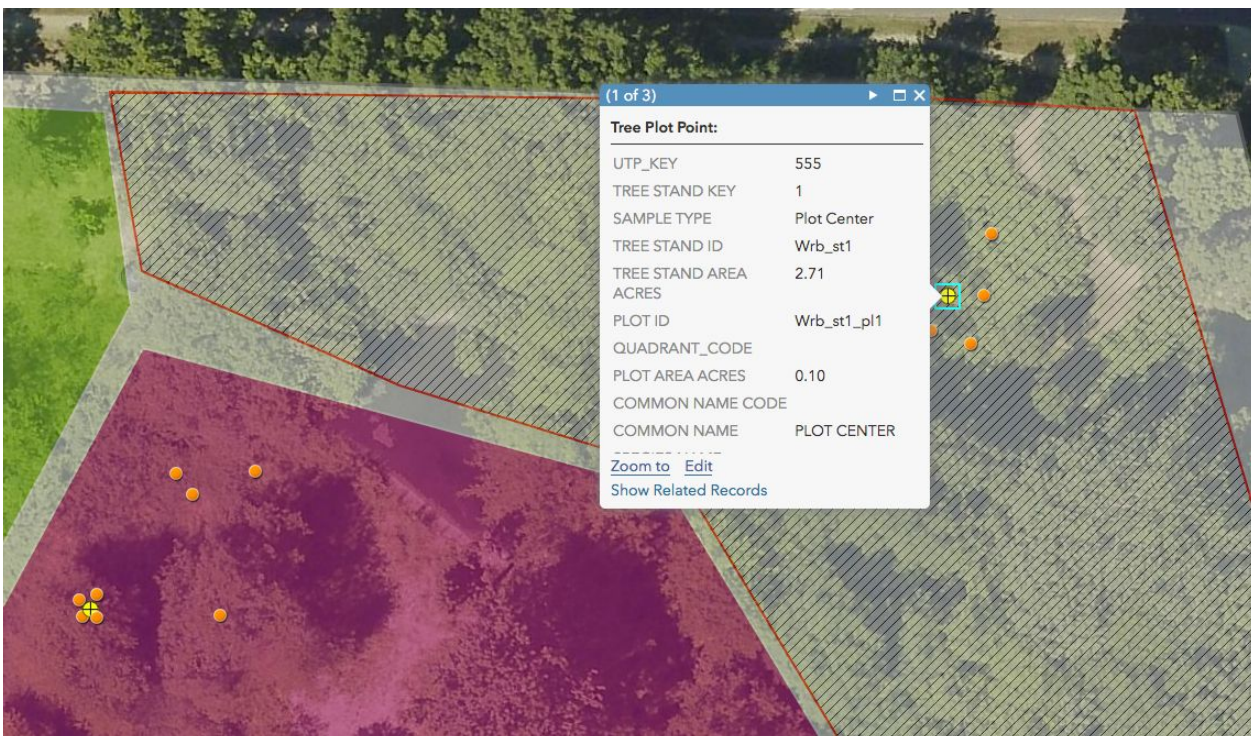


Figure 49: Example of Plot Status method design:
Sample-plot centers, within a tree-stand polygon, are determined through a random-sampling method. Plots are circular and 1/10th of an acre in area - with a radius of 33'. Plots are divided up into 4 quadrants (NW, NE, SW, SE) and the individual tree in each quadrant that is nearest to the plot center is measured and mapped. This is repeated for each tree species present within the quadrant. Total canopy cover at the plot center is determined using a densiometer. and relative contribution to canopy of each tree species within the plot is also determined.