Urban Forestry Management Plan –

Canopy and Forest Structure Analysis Summary report

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Submitted to:

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Executive Summary

The City of Bellingham is currently in the process of developing a comprehensive Urban Forestry Management Plan to strategically manage a healthy and desirable urban forest. As part of Phase 1 of developing this Plan, existing forest conditions were assessed by Diamond Head Consulting. The work included a tree canopy assessment, canopy change analysis, and forest structure analysis. This report describes the methodology, results, limitations, key findings, and recommended next steps for three tasks in Phase 1 including:

- **Task 1A: Tree Canopy Assessment** – Estimated the total canopy cover using LiDAR for 2006, 2013, and 2018. Overall, Bellingham's canopy cover for 2018, including City and the Urban Growth Area, had an estimated 42% tree canopy cover. The canopy cover within the City boundary was estimated at 40% canopy cover in 2018.
- **Task 1C: Canopy Change Analysis** – Compared canopy cover between 2006, 2013, and 2018 for the City, Urban Growth Area, and both areas combined. Overall, canopy cover has remained relatively stable for the past 12 years. The highest canopy cover by management unit is found on all City-owned land (75%) and the lowest within the rights-of-way (26%). On average, neighborhoods in northern Bellingham have lower canopy cover than the average. Southern neighborhoods tend to meet the average canopy cover.
- **Task 1D: Forest Structure Analysis** – Developed using 2013 LiDAR data to estimate coniferous and deciduous species, ages, and the vertical and horizontal complexity of forested stands. Generally, forests in northern Bellingham are dominated by young, primarily deciduous forest and in southern Bellingham dominated by older, taller, and more structurally-diverse forested stands.

The findings outlined in this report will inform the next phases of developing Bellingham's Urban Forestry Management Plan. Phase 2 will engage the community to understand values, goals and objectives, and Phase 3 will involve developing the Plan.

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1.0 Introduction

The City of Bellingham is a community of more than 90,000 residents that stretches over 28 square miles, with an additional 8 square miles of Urban Growth Area (UGA). The City manages an expansive urban forest which includes several thousands of acres of forest and thousands of street trees. Bellingham's urban forest is a valued asset within the community, as recognized in the City's Comprehensive Plan vision and its Tree City USA status.

In this context, the City is creating an Urban Forestry Management Plan (UFMP) as a strategic plan to help maintain a healthy and desirable urban forest through well-coordinated, consistent, efficient, and sustainable long-term urban forest management. The UFMP will encompass all trees, in forests and elsewhere, within City limits and the Urban Growth Area (UGA).

The City of Bellingham contracted Diamond Head Consulting (DHC) to assess existing forest conditions as part of Phase 1 (Assessment) of the City's UFMP. This report describes the methodology and results for:

- Tree Canopy Assessment: The main outputs of this task were canopy cover maps showing existing canopy coverage, under-forested areas, and noxious weed-threatened forest.
- Canopy Change Analysis: This task involved comparing canopy cover change over time using imagery from 2006, 2013 and 2018.
- Forest Structure Analysis: This task involved the stratification of natural forest areas into classes of young to old forest, with attributes for coniferous/deciduous, height class and multi-strata.

The following sections describe the methodology used to complete each task, followed by the results and a brief discussion of limitations and key findings.

2.0 Methodology

2.1 Tree Canopy Assessment

DHC estimated canopy cover for the City of Bellingham in 2006, 2013 and 2018 by producing wall-to-wall canopy mapping from a combination of LiDAR (2006 and 2013 only) and four-band orthoimagery (all years). The complete process and methods for creating the geospatial canopy layers are illustrated in Figure 1 and detailed in Appendix 1. The assessment included mapping current canopy throughout the City of Bellingham and Urban Growth Area (UGA).

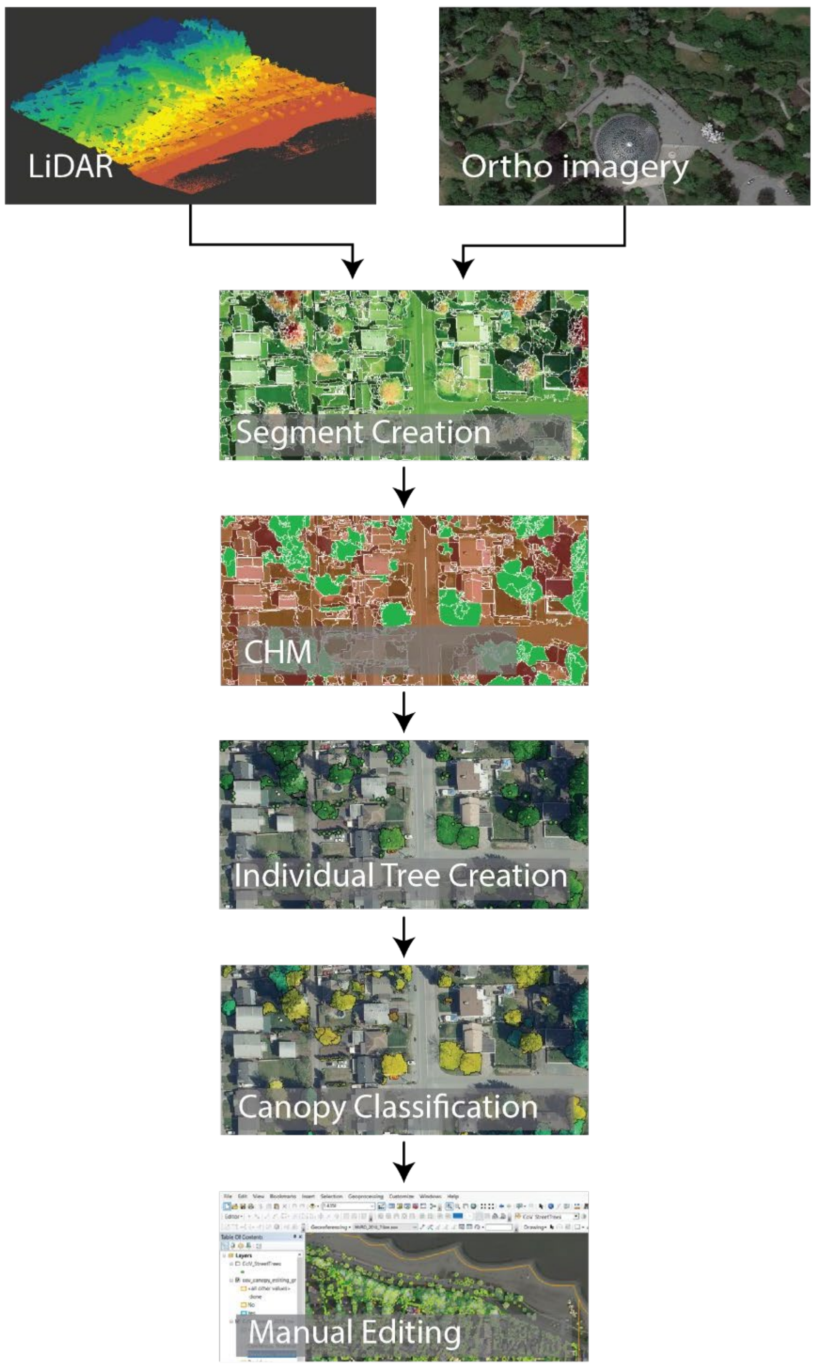

Figure 1. Key steps in generating wall-to-wall mapping of canopy for the City of Bellingham.

2.1.1 Canopy Change Between 2006, 2013 and 2018

ESRI's ArcGIS Pro software was employed to run multiple combinations of erase functions in order to quantify gain/loss between the three comparison years (2006, 2013, and 2018). The GIS software was also utilized to run intersect functions between the canopy datasets and the summary areas (i.e. municipal boundaries, zones, neighborhoods, sub-watersheds, grids, etc.) in order to gain additional insight into the distribution and finer-scale changes of Bellingham's canopy. The summary zone dataset that contains information pertaining to parks, roads, and private lands was derived from an ownership GIS dataset received from the City.

2.1.2 Assumptions and Limitations of the Tree Canopy Assessment

The following assumptions and limitations are described for the tree canopy assessment and change detection:

- The accuracy of the crown delineation algorithm depends on the shape of the canopy. Coniferous trees were detected with higher accuracy compared to deciduous trees, which are broader, contain multiple local apexes, and do not have the defined, conical shape that coniferous trees exhibit.
- Due to the lack of infra-red spectral information for the 2006 orthoimagery (the reflection of light between deciduous and coniferous trees is apparent in the infrared band), the accuracy of the 2006 classification was limited at a fine scale and should be used as a broad guideline only. However, larger groups of coniferous and broad-leaved crowns are well-differentiated.
- There are limitations inherent in our analysis due to data quality, time and budget constraints. Subjective differences among photo interpreters will also have a small effect on the consistency of manual edits across the city, though quality checks have been completed.
- More process-oriented limitations include the over-segmentation of broad-leaf canopies, and the omission of newly planted trees from the canopy model. The over-segmentation of broad-leaf crowns is challenging to avoid when working with deciduous trees at a fine spatial resolution – especially where mature tree canopies overlap.
- Segmentation is more accurate for conifers, due to the apical dominance that many coniferous species exhibit – a trait that often leads to a conical growth form with a single leader. Broad-leaved crowns, however, may contain many local apexes, especially at a fine scale. This is exacerbated, for example, when powerline pruning bifurcates a crown and where mature crowns overlap. From an aerial perspective it can be difficult to separate individual crowns all extending from the same trunk. The over-segmentation of broad-leaf crowns means that caution should be applied when using segments to estimate the number of trees within the city, and ground truthing should always be used to confirm or reject tree counts.
- The 2013 canopy product may under-represent deciduous canopy extents because:
  - 2013 orthoimagery contains areas of low-contrast lighting which makes deciduous canopy areas look spectrally "muddy".
  - 2013 LiDAR was captured in a leaf-off period of March 26-30; leaf-off LiDAR under-represents deciduous canopy extents.
  - 2013 LiDAR has higher point density than 2006, resulting in more precise canopy edges.
- The 2006 canopy product is assumed to be a reasonable representation of deciduous canopy areas but may slightly overestimate canopy because:

  - 2006 orthoimagery shows the deciduous canopy more clearly.
  - 2006 LiDAR was captured in a leaf-on period during late Spring and Summer of 2006, and thus captures the full canopy extent of deciduous trees.
  - 2006 LiDAR was lower point density than 2013 and therefore generalizes canopy edges and may slightly overestimate canopy extents.
- The 2018 canopy product is assumed to be a reasonable representation of deciduous canopy but may slightly overestimate canopy because:
  - 2018 orthoimagery shows the deciduous canopy more clearly and therefore compensated for the underestimates of canopy extent in the 2013 LiDAR.
  - 2013 LiDAR was used as an input to help distinguish between trees and shrub/grass in the 2018 imagery. However, the canopy detection still captured non-trees in some locations. Extensive manual cleaning was used to eliminate non-trees.

2.2 Forest Structure Analysis

The forest successional classes broadly describe how forest characteristics change as they become older, larger and more structurally diverse. Forest stands were mapped as polygons based on similar composition of coniferous or deciduous species, approximate ages, and vertical and horizontal complexity. The forest structure analysis was developed using the 2013 LiDAR data because it was the most recent LiDAR data available.

After mapping forest polygons, each polygon was given descriptive attributes. The descriptive attributes included:

1. Successional stage (Table 1):
   - Forests structure was described using six classes of forest succession including shrub, pole-sapling, young (with subcategories of short and tall), mature and old forests. The forest succession classes broadly describe how forest characteristics change as they become older, larger, and more structurally diverse. Definitions of forest successional stage used to describe Bellingham's forest structure were based on the forest industry standards from BC[1] and the USDA[2].
   - The successional stage class of Young Forest includes a broad range of forests in Bellingham. It was decided to divide this Young class into the two subcategories of Short and Tall to better understand how these forests differ across the landscape. Forest structure classes are summarized in Table 1 and Figure 2.
   - Forest polygons were assigned one of the six forest succession stages based on the canopy height model, an analysis of frequency distributions of height and height percentiles combined with any available ancillary forest inventory data. Age class was confirmed at some sample locations through ground truthing and taking wood cores to age trees.
   - Many forest areas in Bellingham have multistoried canopies, or areas with trees of different ages. These areas likely experienced multiple stand disturbances, leading to a mix of tree ages. Due to the large size of the forest areas classified (necessary for a city-wide scale analysis), there may be intermixed pockets of trees that are older or younger within an area. The successional stage classes are broad, and large forest areas were assigned to a single class to represent the most dominant age class, height and structure for each large.
   - The coarse resolution of the analysis was suitable to answer broad questions about the quantity, composition, and structure of forest areas in Bellingham for the citywide plan..
2. Type:
   - Deciduous (greater than 70% deciduous), coniferous (greater than 70% coniferous), mixed classes were determined from the canopy model species classification, orthophotos and ground truthing.

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[1] BC Ministry of Forests, 2010. Land Management Handbook #25. Field manual for describing terrestrial ecosystems 2nd edition.

[2] USDA Forest Service, 2012. A stage is a stage is a stage…Or is it? Successional stages, structural stages, seral stages.

3. Height classes:
    - Six height classes (one for each forest structure class in Table 1) were determined from LiDAR data. LiDAR provides accurate heights of individual trees in forest stands. The average height assigned to each forest area was an average of the height of every tree, at all canopy levels, across the entire forest stand area. See Appendix 2 for details.
4. Forest health factors:
    - Forest health factors in the last 10 years were based on available WDNR aerial surveys and ground-truthing.
5. Multi-Strata:
    - No (only one canopy stratum is detected), yes (more than one canopy strata is detected) were based on an analysis of frequency distributions of height and height percentiles combined standard deviation and skewness height rasters, and any available ancillary forest inventory and/or park asset data.

The GIS methodology steps used to attribute the forest polygons are provided in Appendix 2.

Table 1. Forest structure class descriptions including approximate height and representative details.

Forest structure class	Approximate height (feet)	Successional status description
Old Forests	148 or more	Stands that are very old with complex structure; patchy shrub and herb understories are typical; regeneration is usually of shade-tolerant species with composition similar to the overstorey; long-lived seral species may be present in some ecosystem types or on edaphic sites. Old growth structural attributes will differ across biogeoclimatic units and ecosystems. These forests are typically greater than 240 years.
Mature Forests	115 to <148	Trees are well established and large in size; stand openings exist and a second cycle of shade-tolerant trees may have become established; shrub and herb understories become well developed as the canopy opens up; habitat features such as standing dead trees and large stems on the ground exist. Forests with these attributes tend to be greater than 80 years old but this varies depending on the species and productivity of the site.
Young Forest Tall	82 to <115	Self-thinning has become evident and the forest canopy has begun to differentiate into distinct layers (dominant, main canopy, and overtopped); trees have vigorous growth and the canopy is more open compared to the Pole/Sapling stage; this stage can begin as early as 20 years old in highly productive stands and can extend to approximately 80 years or more depending on when the stand structure becomes more complex.
Young Forest Short	33 to <82	
Pole Sapling Forests	10 to <33	Trees > 10 ft tall, typically densely stocked, and have overtopped shrub and herb layers; vertical structure are not yet evident in the canopy; these stands are usually younger than 20 years old.
Shrub	<10	Early successional stage or a shrub community maintained by environmental conditions (e.g., wet soils, cold air accumulation) or disturbance (e.g., avalanche track); tree cover sparse, but tree seedlings and advance regeneration may be

Forest structure class	Approximate height (feet)	Successional status description
		abundant; either dominated by shrubby vegetation, or if sparsely vegetated overall, shrub cover and stature characterizes the community as a shrubland.

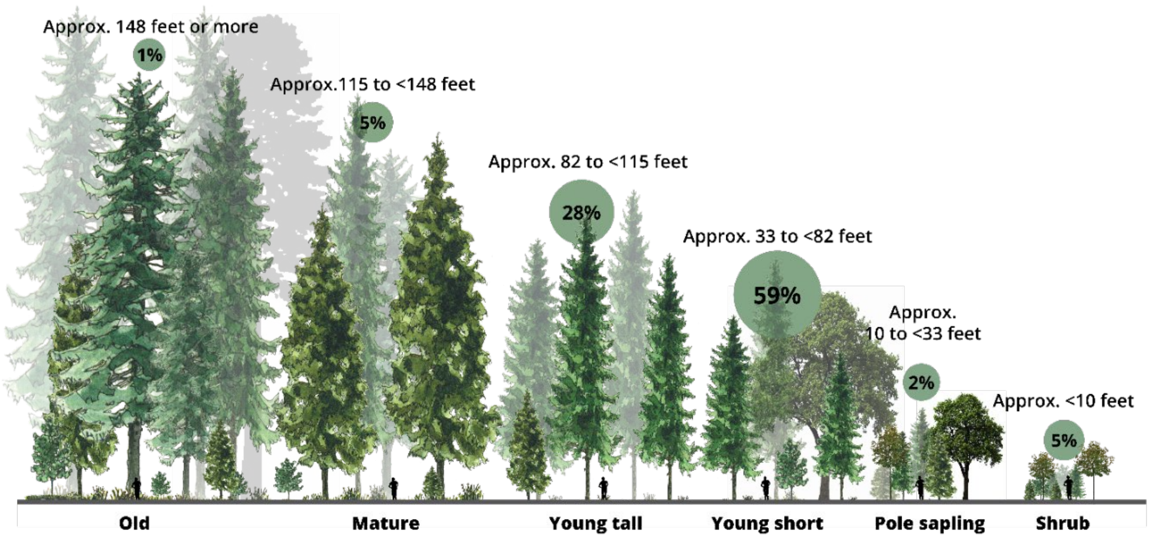

Figure 2. Composition of overall forest structure classes and criteria used in assessing the six forest structure classes.

To refine and confirm the analysis, representative forested areas were visited on the ground. Core wood samples were taken at 16 representative ground sampling plots across the City to estimate tree ages within each successional stage. In addition, the analysis was checked using orthophotos and a review of historic images that show previous land clearing activity to provide further context for the age of forest stands.

2.2.1 Assumptions and Limitations of the Forest Structure Analysis

The following assumptions and limitations are described for the Forest Structure Analysis:

- The forest structure analysis was developed using the 2013 LiDAR data, therefore height information was limited to that time period.
- There are limitations to using height as a proxy for forest age because different species grow at different rates and productivity differs between sites.
- In some forests, older trees were mixed in with a younger generation of trees. This was the case where forests have been partially cleared or thinned in the past. In these cases, the stand was designated a successional stage that best reflected the majority of trees in the forest stand.
- Confirming older trees was difficult due to the limitations of taking wood cores. In general it is difficult to extract a complete sample from large diameter trees. The central part of the tree can be decayed or the increment borer may not hit the center of the tree. In these cases, the ages were counted for what could be extracted and then the missing central part of the core was estimated based on the radius of the tree and the average width of the closest rings.
- A minimum polygon size of five acres was used to establish forest type boundaries in continuously forested areas. Five acres was consistent with the Forest Block definition used in the Bellingham

Habitat Restoration Technical Assessment Report (City of Bellingham, 2015b). Smaller forest stands that were technically disconnected from larger stands but only by very small gaps were merged in with larger adjacent blocks. All remaining polygons under 0.25 acres (~0.1 Ha) were deleted.
- The coarse resolution of the analysis was suitable to answer broad questions about the quantity, composition, and structure of forest areas in Bellingham for the citywide plan. However, the results of this initial analysis are not suitable for planning at smaller scales, such as the site or park scale, because those plans would require a higher resolution of mapping and field inventory to capture differences in structure within forest stands.

2.3 Forest Potential Analysis

The forest potential analysis identified areas that are undeveloped (i.e., forest, grass or non-vegetated areas) but have not reached their full forested potential in terms of forest cover or stocking with long-lived, climate suitable species. The analysis was assessed from two perspectives:

1) **Forest restoration areas** that represent potential opportunities to enhance immature forest stands or reduce presence of noxious weeds that may impact tree growth.
2) **Grass and non-vegetated areas** that represent areas that are undeveloped and unforested and may have potential for tree planting.

2.3.1 Potential Forest Restoration Areas

This analysis included identifying forests that have not reached their full potential, on all lands and grass areas within riparian buffers. DHC used the forest structure polygons as the starting point for the analysis. Any shrub, pole sapling, or young forest short polygons that were deciduous dominated (based on the forest structure analysis) were identified as under-forested. Deciduous stands were prioritized because deciduous trees typically colonize sites first following disturbance and then eventually die out as longer-lived conifers gradually become dominant. Underplanting conifers into these forests can help to ensure that the conifers are present in the stand as the deciduous trees start to decline and die. Grass and non-vegetated areas within riparian buffers were also include in the analysis because they may be potential opportunities to restore forest cover.

The analysis also captured forest polygons with the presence of noxious weeds that may impact tree growth. English ivy (*Hedera helix*) and clematis (*Clematis spp.)* were chosen as the noxious weed species of concern to capture because of their potential to blanket trees and supress tree growth. The analysis used a City-provided Noxious Weed Map that identified known infestations ≥ 0.25 acres in size of Class A, Class B, or Class C weeds listed on the 2020 Whatcom County Noxious Weed List (Whatcom County Noxious Weed Control Board, 2020) any forest structure polygon overlapped an English ivy or clematis inventory polygon, or a Washington State crowdsourced (Washington State Department of Agriculture, 2021) ivy or clematis invasive point, then it was also identified as an area with noxious weeds that may impact tree growth.

2.3.2 Grass and Non-Vegetated Areas

DHC used the City's 2013 vegetation model results – Vegclass raster layer to identify grass and non-vegetated areas that may have the potential to support tree planting in the future. The raster layer was re-classified as non-vegetation & grass (1) and others (0) before converting to a vector polygon layer. Roads, parks facilities (e.g., sport fields, active use areas, etc.), impervious surfaces, buildings, and the 2018 canopy layer were erased from the grass and non-vegetated areas if they overlapped; these areas would not have the potential to support tree planting. The grass and non-vegetated areas where then summarized within each of the following management unit categories:

- Private property by neighborhood
- ROW
- City-owned property
  - Community Parks
  - Neighborhood Parks
  - Special Use Sites
  - Open Space
  - Undeveloped ROW
  - Other
- Other public

Finally, DHC generated coarse estimates of the number of trees that could potentially occupy these spaces if planted. Estimates for number of potential trees were calculated by management unit and tree soil area (assuming average 24 inch depth) based on the Bellingham's City Centre Street Design Standards (City of Bellingham, 2015a), which recommend soil areas for:

1. Large trees (50 ft mature canopy): recommend soil area of 750 ft^2
2. Medium/large trees (40 ft mature canopy): recommend soil area of 600 ft^2
3. Medium trees (35 ft mature canopy): recommend soil area of 500 ft^2
4. Small trees (20 ft mature canopy): recommend soil area of 300 ft^2

The number of trees that could potentially be planted based on these recommended soil areas was calculated from largest to smallest meaning that all sites larger than 750 ft^2 were assumed to be large trees only, then sites between 600 ft^2 and 749 ft^2 were medium/large trees only and so on until only small tree sites remained. Polygons smaller than 300 ft^2 were not considered plantable. This analysis provides an estimate of the relative capacity of different land uses to support tree planting and potential canopy gain. While these areas provide a coarse relative estimate of the potentially available planting areas in the City, other considerations including site constraints and usage conflicts and future land use would need to be considered to refine these areas into actionable planting opportunities.

2.3.3 Forest Potential Analysis Assumptions and Limitations

The following assumptions and limitations are described for under-forested areas:

- Due to limitations of the data in distinguishing between species, some areas may be misidentified as candidates for restoration planting (e.g., young regenerating forest rather than shrub) therefore this dataset will require further review and refinement to incorporate local knowledge.
- The grass and non-vegetated areas data is based on LiDAR data from 2013, and therefore may have changed in some areas.
- The estimate of potential trees assumed **all** grass and non-vegetated areas, other than those under active use, could be converted to forest. In reality, not all grass and non-vegetated areas can be converted to forest due to under or overhead utilities, transportation planning, park master plans, private land ownership, and other constraints; therefore the absolute planting areas are a significant overestimate. However, these areas provide an indication of the relative potential for each management unit to support additional tree canopy and provide a basis of grass and non-vegetated areas that could be refined into planting opportunities for operational use with further analysis.
- The number of potential trees estimate assumes that large trees would be planted preferentially over medium trees, which may not reflect reality, therefore the number of tree opportunities per area may be underestimated; however the anticipated canopy outcomes would be similar because the analysis would assume more medium trees would be planted.

3.0 Results

3.1 Tree Canopy Assessment

Bellingham's land (including City and Urban Growth Area) had an estimated 42% average tree canopy coverage in 2018. The canopy cover within the City boundary was estimated at 40% canopy cover in 2018.

As in most cities, Bellingham's tree canopy is not evenly distributed. Figure 2 maps canopy cover in 5 acre grids and shows that canopy cover in 2018 was below 15% in some areas and exceeded 45% in other areas. Differences in tree canopy cover across the city are likely to be driven by factors such as land use, and the location of parks and natural features. Canopy cover was lower than average in the more developed north-central, north-eastern, and central core areas of the city. Canopy cover was higher than average in parklands, along riparian corridors and in the Urban Growth Area (UGA).

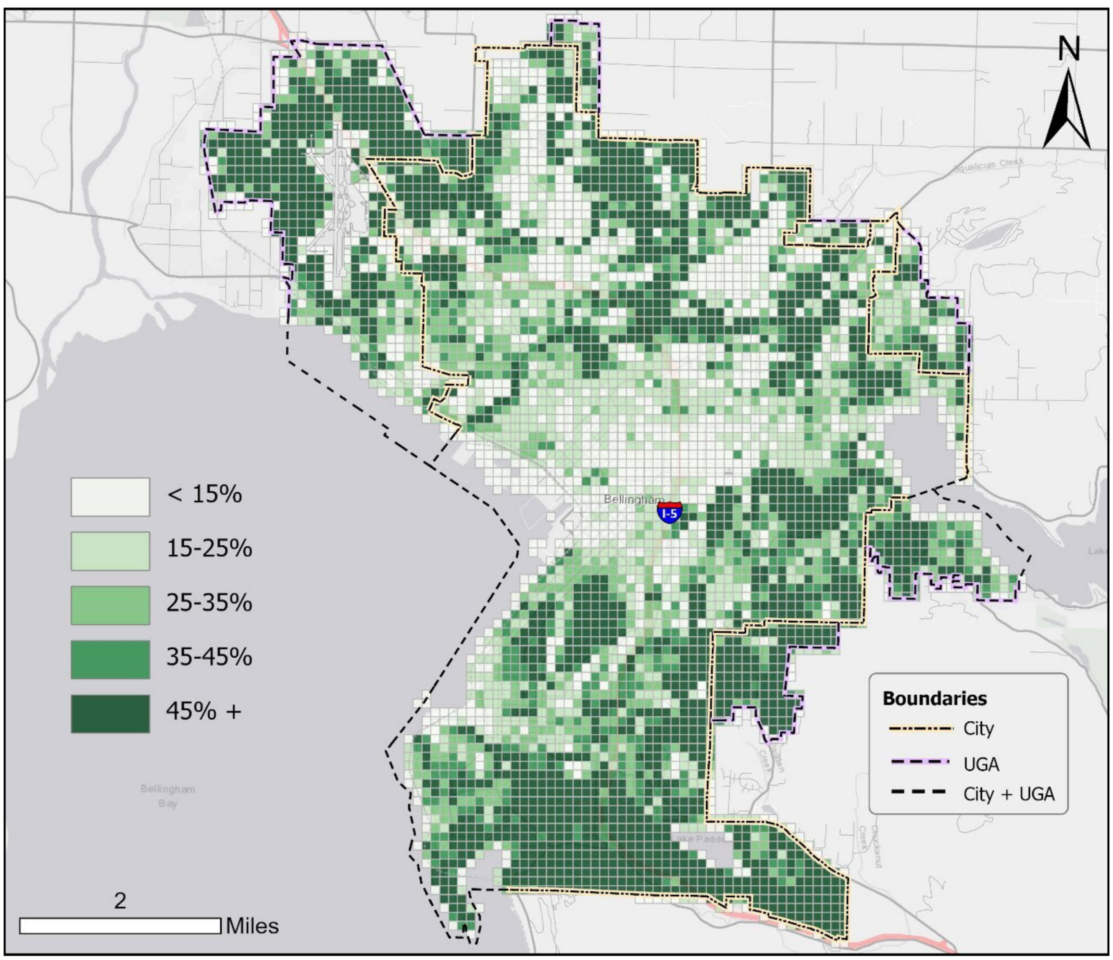

Figure 3. Canopy cover percentage grid distribution in 2018.

3.2 Canopy Change Between 2006, 2013 and 2018

Figure 3 graphs percent canopy cover over the City, UGA and City + UGA for each year measured. Minimal changes in canopy cover percentage were detected between 2006, 2013 and 2018. Overall, the canopy cover within the City + UGA was estimated at 41% tree canopy cover in 2006, 40% canopy cover in 2013, and 42% canopy cover in 2018.

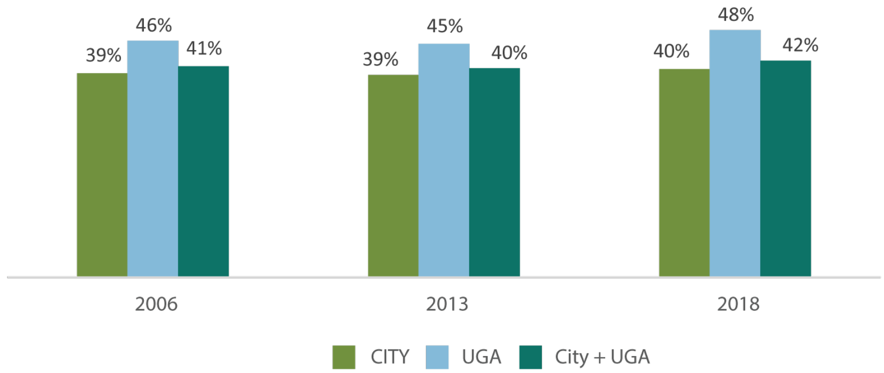

Figure 4. Historical change in canopy cover from 2006 to 2018.

The small differences between the total percentage canopy reported in 2006, 2013 and 2018 may be due to the resolution of the LiDAR and imagery datasets available for the analysis, rather than differences in tree canopy, as noted in section 2.2.2. This assertion is supported by the:

- Accuracy assessment conducted on the 2013 LiDAR, which found that the canopy polygons had high accuracy as a representation of the canopy captured by the LiDAR. However, review of the 2013 canopy polygons in comparison to 2006 and 2013 found that the LiDAR data underestimated deciduous tree canopy because it was flown when those trees were not in leaf. Nothing could be done to correct seasonal differences, which are inferred to be the reason for the slight drop in canopy is evident in 2013.
- Extensive manual editing performed on all three datasets to remove artifacts like building roofs, shadows, and non-tree objects that were mistakenly captured by the segmentation algorithm so each dataset is a reasonable representation of the canopy captured by the LiDAR and shown on the orthophoto for each year.

While the citywide results indicate Bellingham's tree canopy was stable overall, substantial areas of both loss and gain were found in each time period (Table 2). Canopy loss and canopy gain were detected in each time period. However, the limitations of the LiDAR and orthoimagery data inputs likely result in an overestimate of the loss between 2006 and 2013 and overestimate of the gain between 2006 and 2018.

Table 2. Canopy Gain and Loss in Bellingham (City and UGA) between 2006 and 2018.

Comparison Period	Loss (Acres)	Gain (Acres)	Net (Acres)
2006 - 2013	1,260	1,180	- 80
2013 - 2018	750	1,080	330
2006 - 2018	1,378	1,622	243

Despite relative stability in city-wide canopy, Figure 4 shows that gain and loss has occurred in different parts of the city. The relative change in each cell was calculated by taking the tree canopy area in 2018, subtracting the tree canopy area in 2006, then dividing this number by the area of tree canopy 2006.

Canopy loss was predominantly due to timber harvesting or clearing for development. Canopy gain was mostly due to reforestation, growth of forested areas or tree planting with development. For example, subdivisions in the Cordata Neighborhood in the city's north end showed significant canopy gain over the last 12 years due to tree planting with the development (Figure 4, Figure 7).

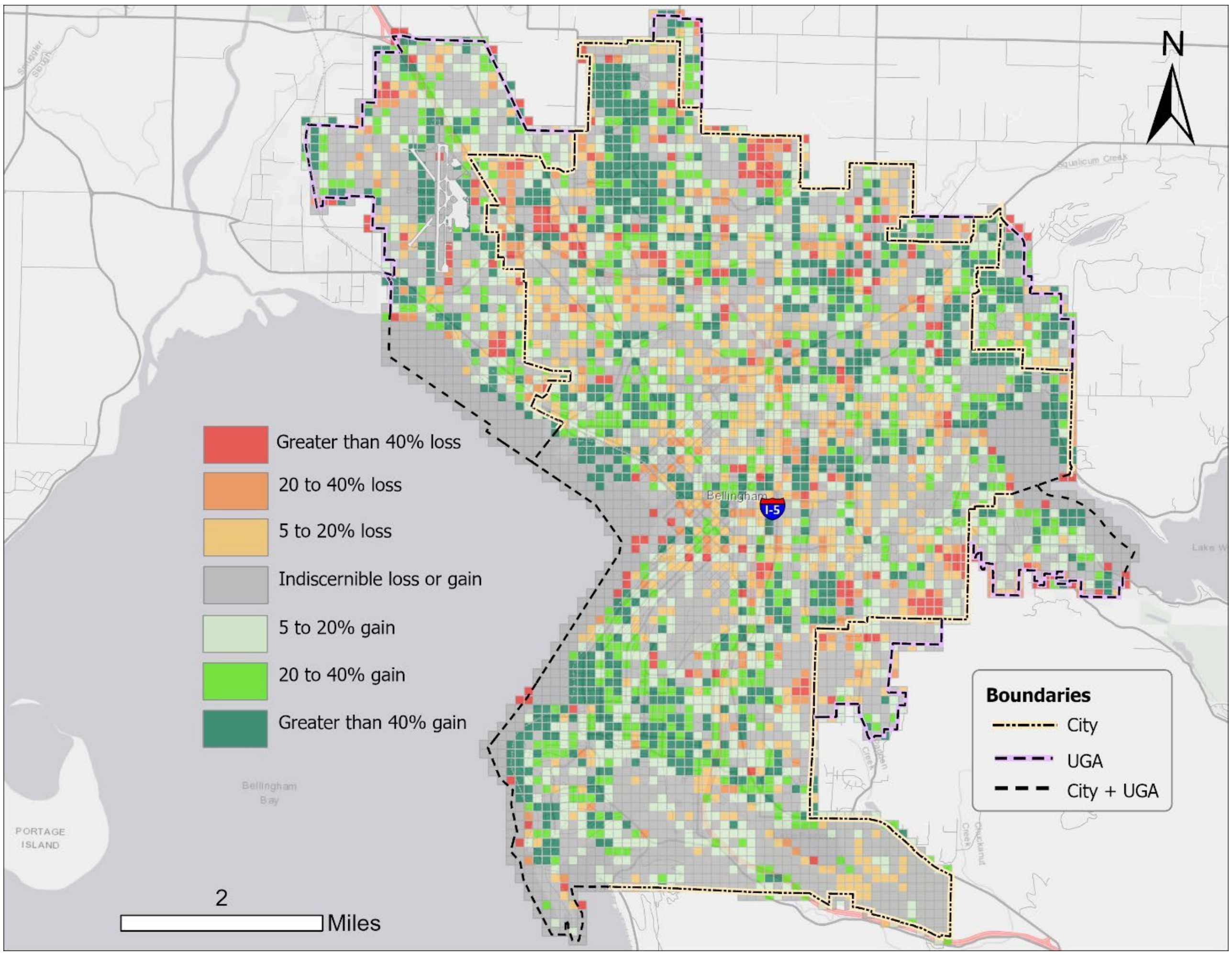

Figure 5. Canopy gain and loss between 2006 and 2018 summarized by 5 acre grids.

Several examples of loss and gain are shown in the following pages. Figure 5 shows an example of an area surrounding San Juan Blvd and Yew St where loss (red) occurred between 2006 and 2013 due to development. Figure 6 shows an example of an area surrounding Fraser St and Woburn St where gain (bright green) occurred between 2006 and 2013 due to canopy growth.

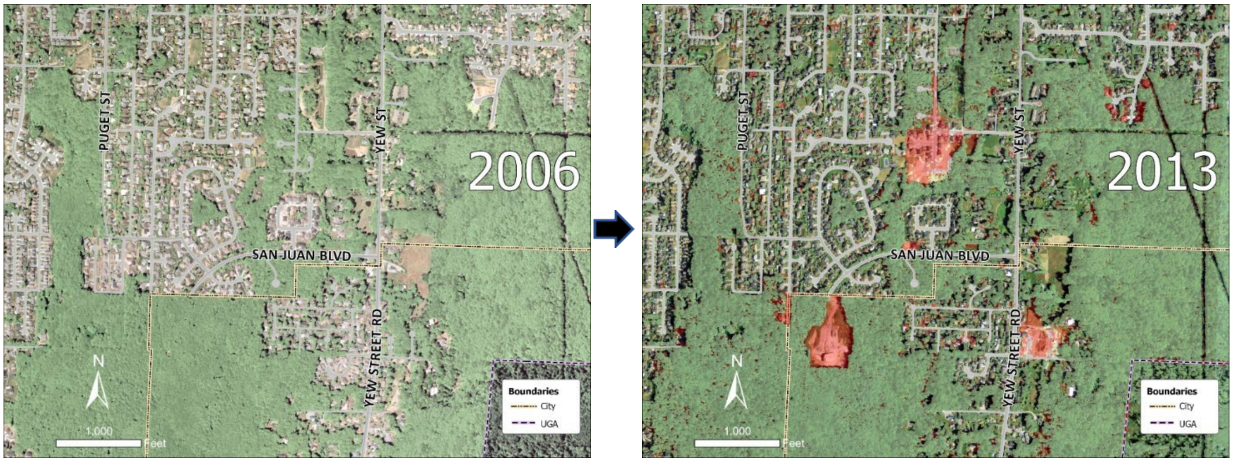

Figure 6. Canopy loss between 2006 and 2013 in an area surrounding San Juan Blvd and Yew St.

Figure 7. Canopy gain between 2006 and 2013 in an area surrounding Fraser St and Woburn St.

Figure 7 and Figure 8 show examples of canopy growth (bright green) between 2013 and 2018.

Figure 8. Canopy growth between 2013 and 2018 new subdivision surrounding Cordata Pkwy and Tremont Ave.

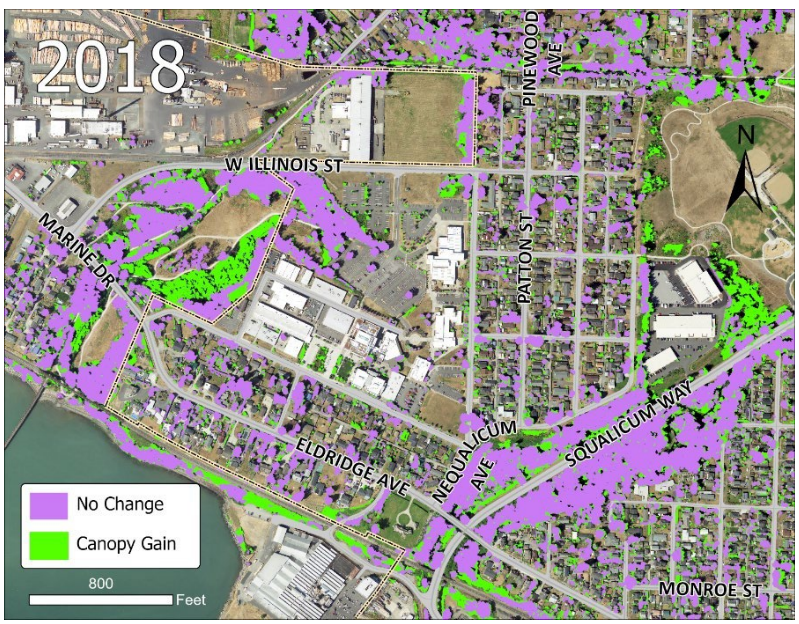

Figure 9. Canopy growth between 2013 and 2018 in the areas surrounding Bellingham Technical College, Squalicum Park, and Little Squalicum Park.

3.3 Canopy Area Summaries

3.3.1 Tree Canopy Summarized by Management Units

Canopy cover was examined over different management units representing differences in ownership and uses (Figure 9). City-owned land supports the highest canopy cover, with City-owned parks and open spaces contributing most of that canopy area. Private land averaged 38% canopy cover and roads had the lowest cover at 26%. The greatest area of tree canopy was found on private land (5,197 acres), followed by City-owned lands (2,243 acres), other public lands (1,157 acres) and roads (982 acres) (Figure 9).

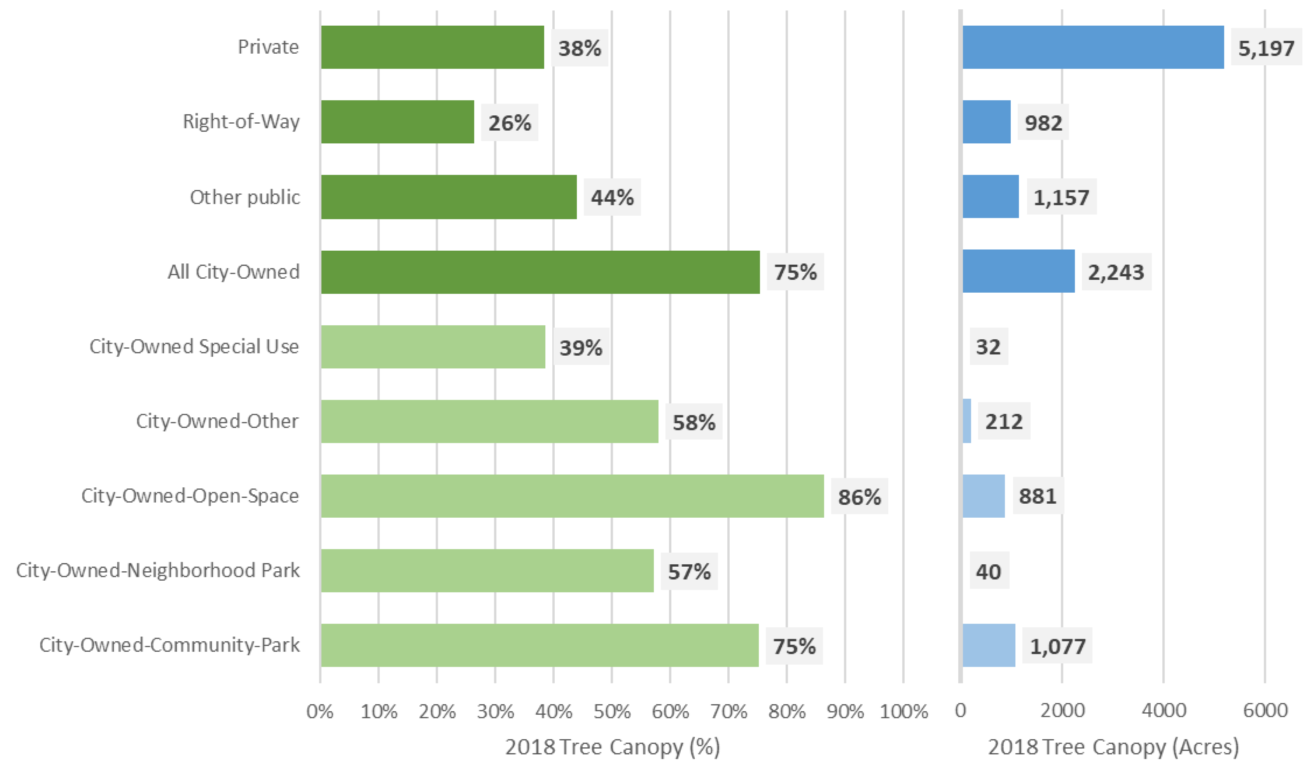

Figure 10. Canopy cover by land use summary areas (City and UGA) in 2018.

Canopy cover has been relatively stable across most management units (Figure 10). Private land and right-of-way have shown the greatest increase in canopy area between 2006 and 2018 (Figure 11), with gains of 86 acres and 117 acres respectively.

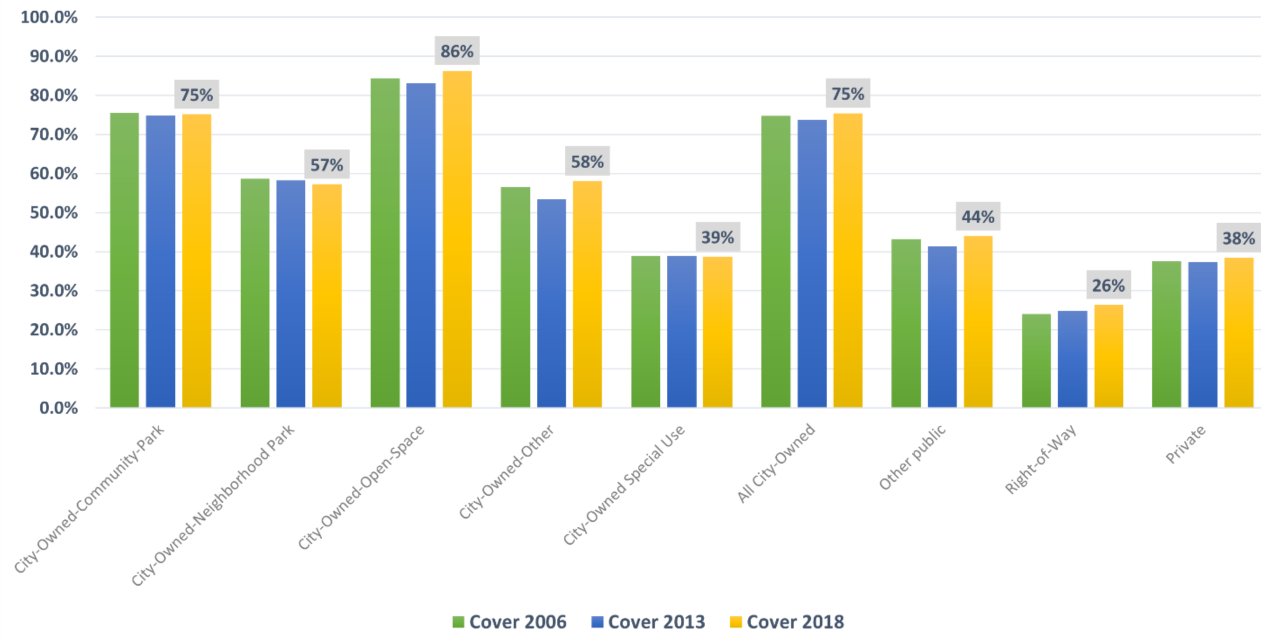

Figure 11. Canopy cover breakdown by summary zone (City and UGA) in 2006, 2013 and 2018.

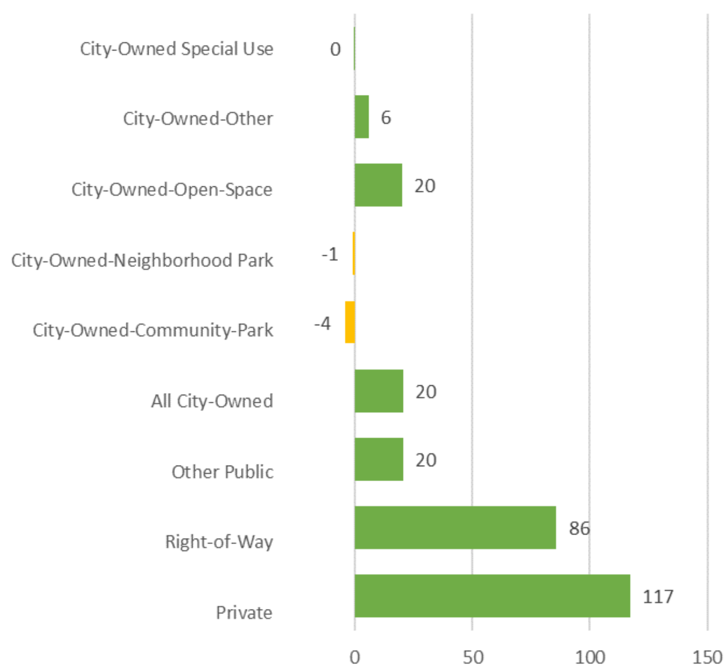

Figure 12. The net area (acres) of gain or loss in each land use summary area (City and UGA) between 2006 and 2018. Net gain is shown in green, loss in orange.

3.3.1 Tree Canopy Summarized by Neighborhoods

Canopy cover varied between neighborhoods in Bellingham. Neighborhoods in the city's core exhibited the lowest canopy percentage, with the City Center neighborhood having only 10% canopy cover (Figure 12). With the exception of King Mountain, neighborhoods in the northern portion of the City tended to have canopy cover below the 42% overall average for the study area (City + UGA) and below the 40% overall average within City limits. Bellingham's southern neighborhoods tended to have above average canopy cover.

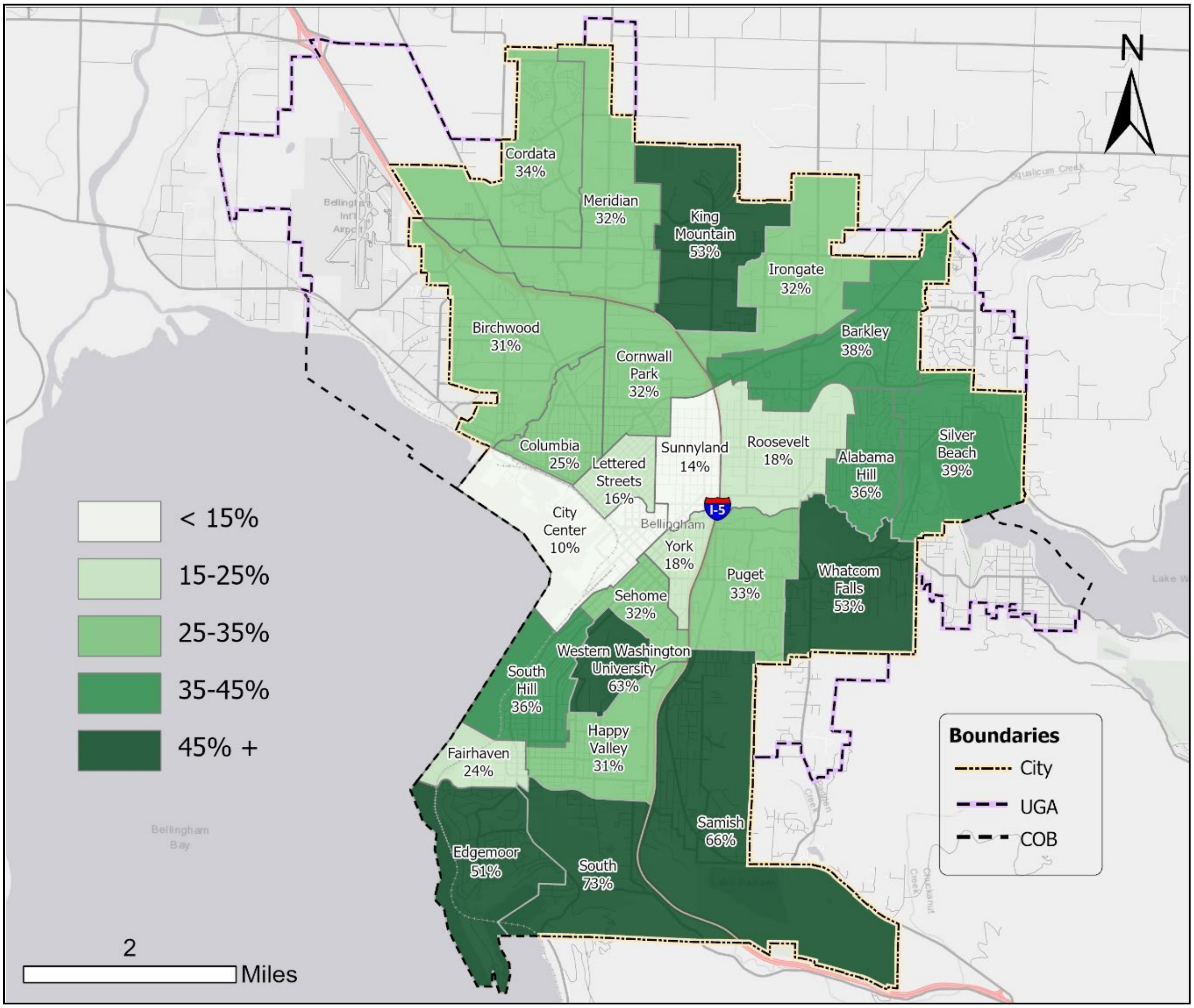

Figure 13. Canopy cover percentage by neighborhood in 2018.

In terms of canopy gain, neighborhoods in the City's southern section like Edgemoor, South, South Hill, and Happy Valley showed consistent growth in canopy cover from 2006 to 2018 (Figure 13, Figure 14). The greatest losses occurred in King Mountain and Whatcom Falls. King Mountain is one of the city's highest canopy cover neighborhoods but is undergoing residential development into forested and rural lands. Whatcom Falls is also a very high canopy cover neighborhood but has lost canopy cover due to residential development and forest harvesting.

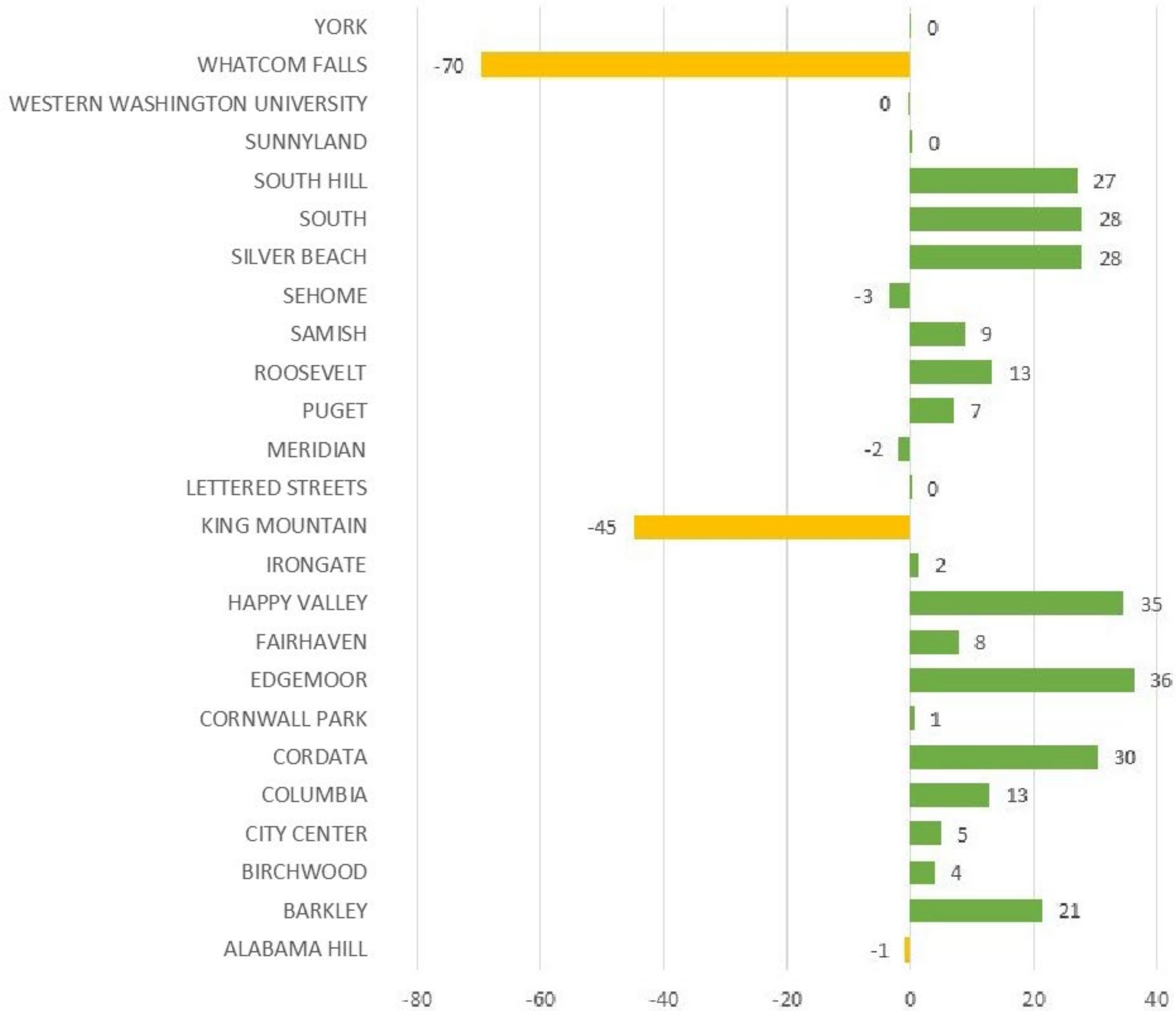

Figure 14. The net canopy cover gain or loss (acres) from 2006 to 2018 in each neighborhood (City only).

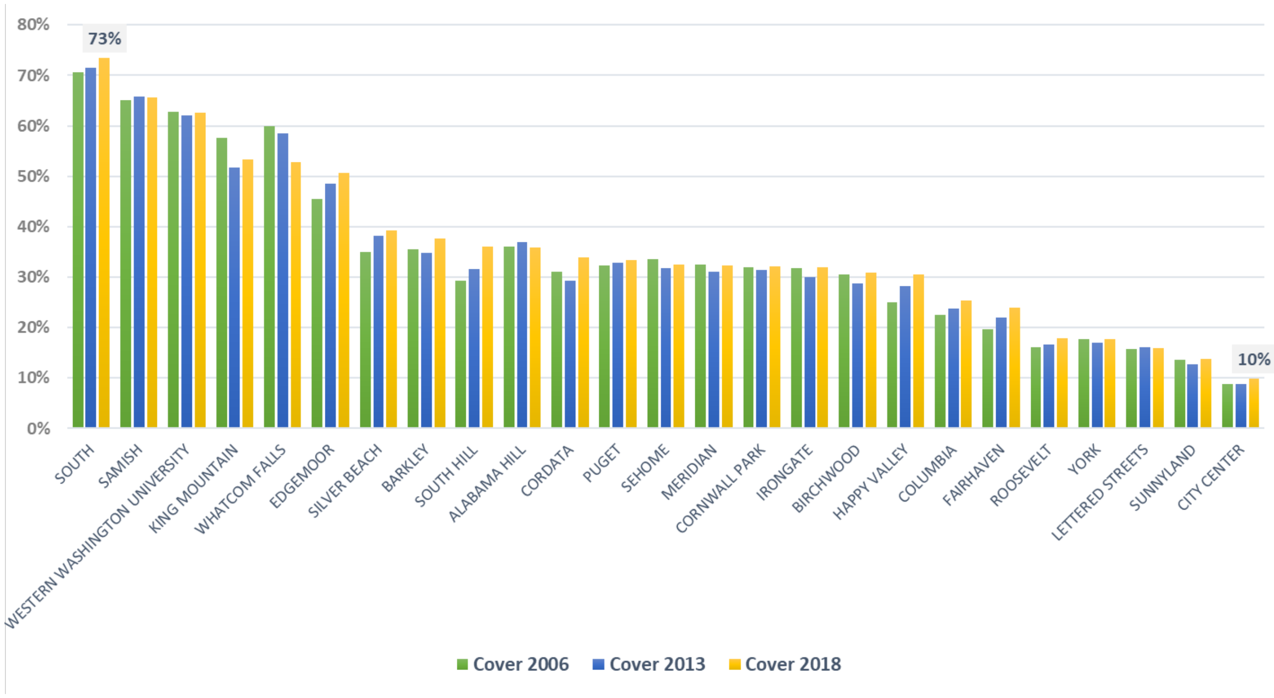

Figure 15. Canopy cover breakdown by Bellingham neighborhood in 2018 (City only), as well as the general canopy trends between 2006 and 2018.

3.3.2 Tree Canopy Summarized by Sub-watersheds

The City of Bellingham contains eight watersheds that drain into a particular stream, river, lake or the bay. Watersheds are further broken into sub-watersheds that drain into smaller streams or waterbodies and then flow into the large watershed feature. Canopy cover has been estimated for each sub-watershed (Figure 15).

Sub-watersheds that span the city's core exhibited the lowest canopy cover. Squalicum Harbor had the lowest canopy cover in the City at 14%, followed closely by Lower Whatcom Creek (20%), Fever Creek (25%), Little Squalicum Creek (26%), and Central Bellingham (28%). Sub-watersheds in the city's south had the highest canopy cover, with Chuckanut Creek having canopy cover of 84%. Upper Baker Creek had the highest canopy cover but only a small portion of the sub-watershed is within the City boundary and so the result may not represent the canopy cover of the whole sub-watershed.

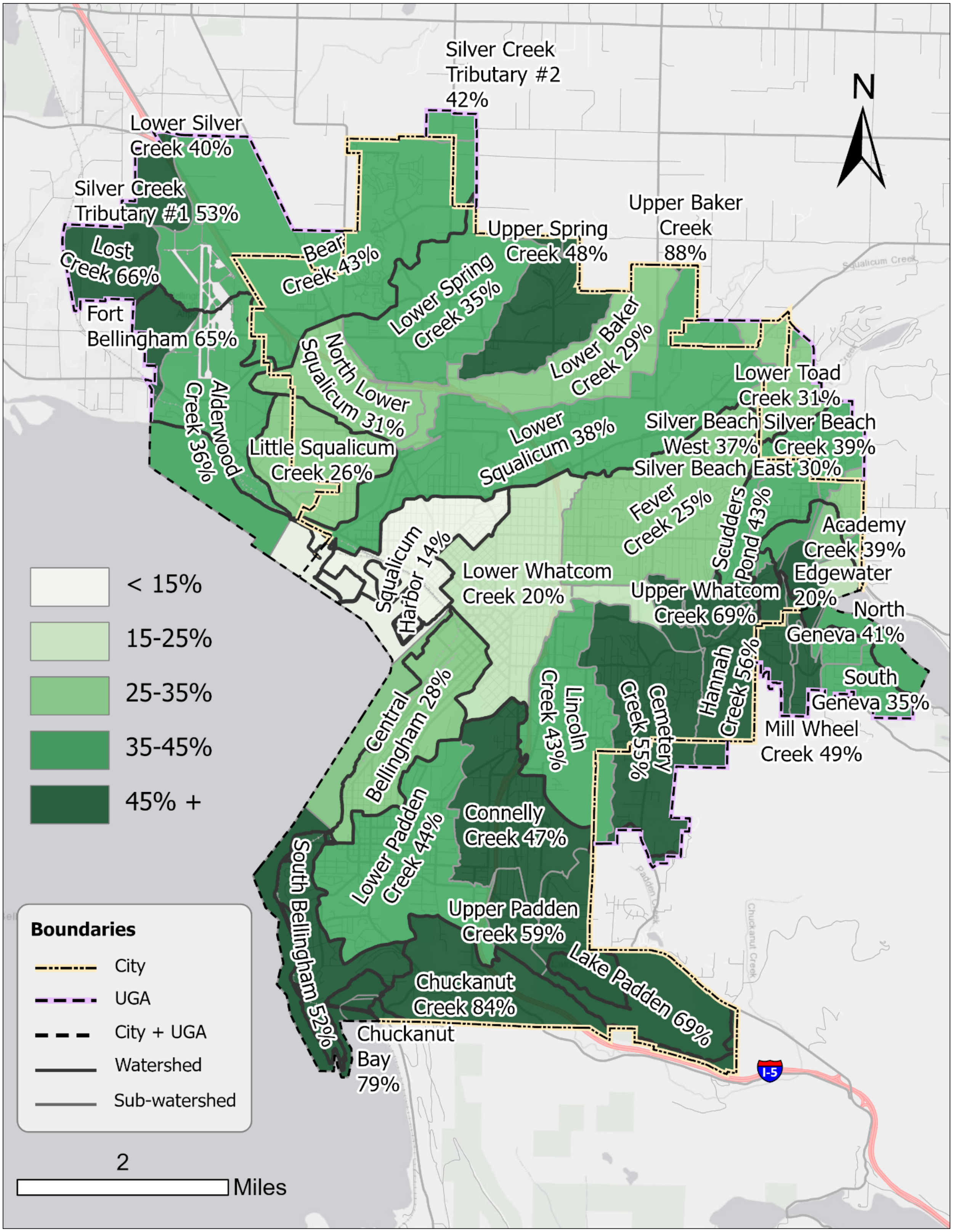

Figure 16. Canopy cover by sub-watersheds in 2018. The highest and lowest canopy cover sub-watersheds are labelled for reference.

The greatest losses in canopy cover between 2006 and 2018 occurred in the City's Upper Spring Creek Sub-watershed and Hannah Creek Sub-watershed (Figure 16). The greatest gain in canopy cover between 2006 and 2018 occurred in Lower Padden Creek (50 acres), closely followed by Bear Creek (44 acres).

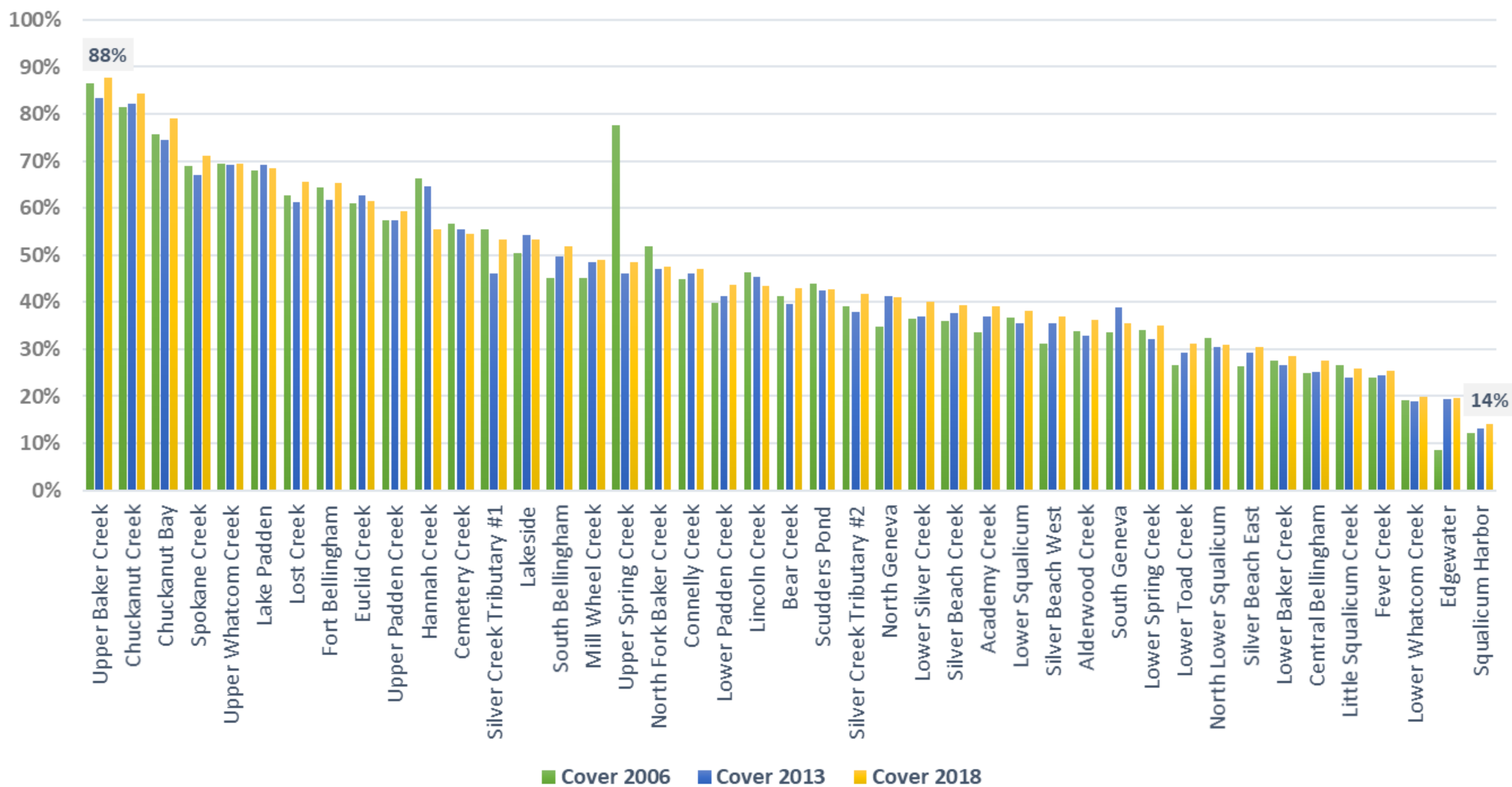

Figure 17. Canopy cover breakdown by sub-watersheds in 2018 (City and UGA), as well as the general canopy trends between 2006 and 2018.

3.3.3 Tree Canopy Summarized by Riparian Zone within each Watershed

Riparian areas in the city averaged 45% canopy or higher in 2018. For the purposes of this assessment, the riparian zones were based on the criteria in Title 16 of the Bellingham Municipal Code in the Critical Areas stream buffer widths section – specifically Table 16.55.500(A). The maximum buffers listed for each stream reach and type (varying between 100 and 200 feet) were used unless they were streams also regulated through the Shoreline Master Program (Title 22 of our BMC), in which case the maximum regulatory zone buffer of 200 feet was used. (Figure 18, Figure 17).

Riparian areas were grouped by watershed to summarize canopy cover. Canopy cover gains between 2006 and 2018 were observed for almost all riparian zones except Little Squalicum Creek, which declined, and Whatcom Creek, which remained stable. Silver Creek watershed had the lowest canopy cover overall at 48% while Chuckanut Creek watershed had the highest at 87%.

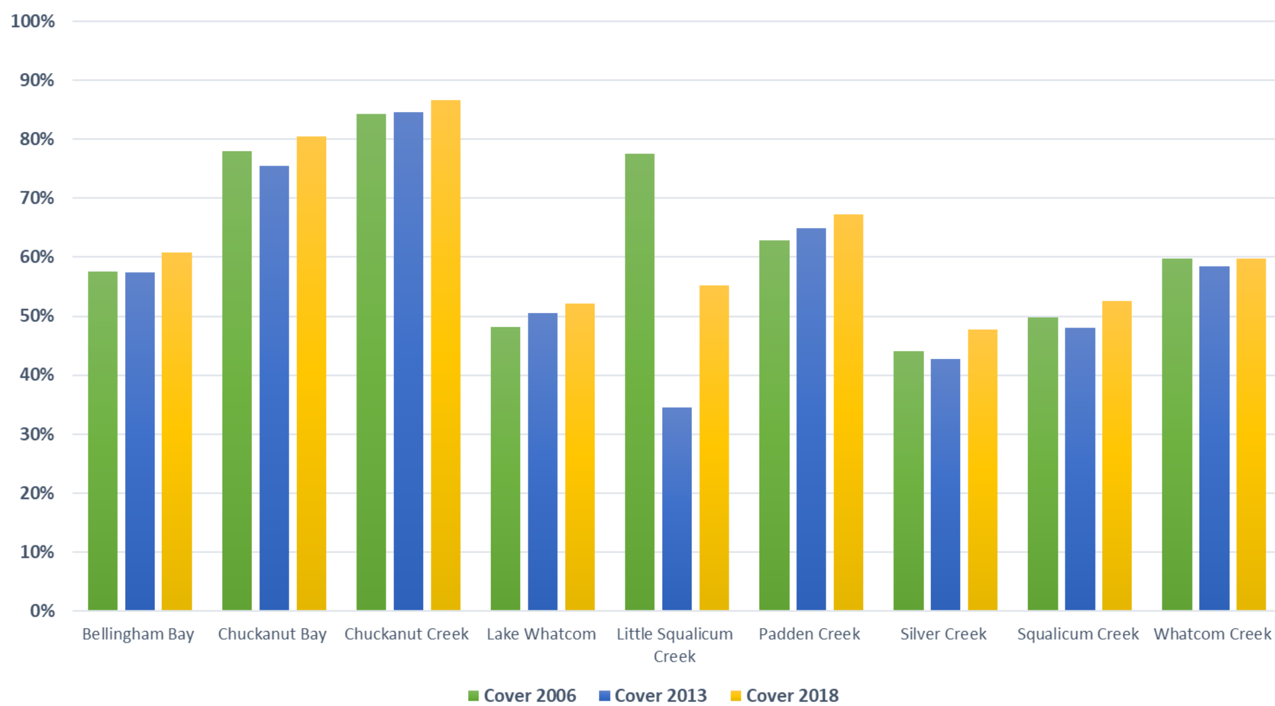

Figure 18. Canopy cover breakdown by riparian areas within each watershed in 2018 (City and UGA), as well as the general canopy trends between 2006 and 2018.

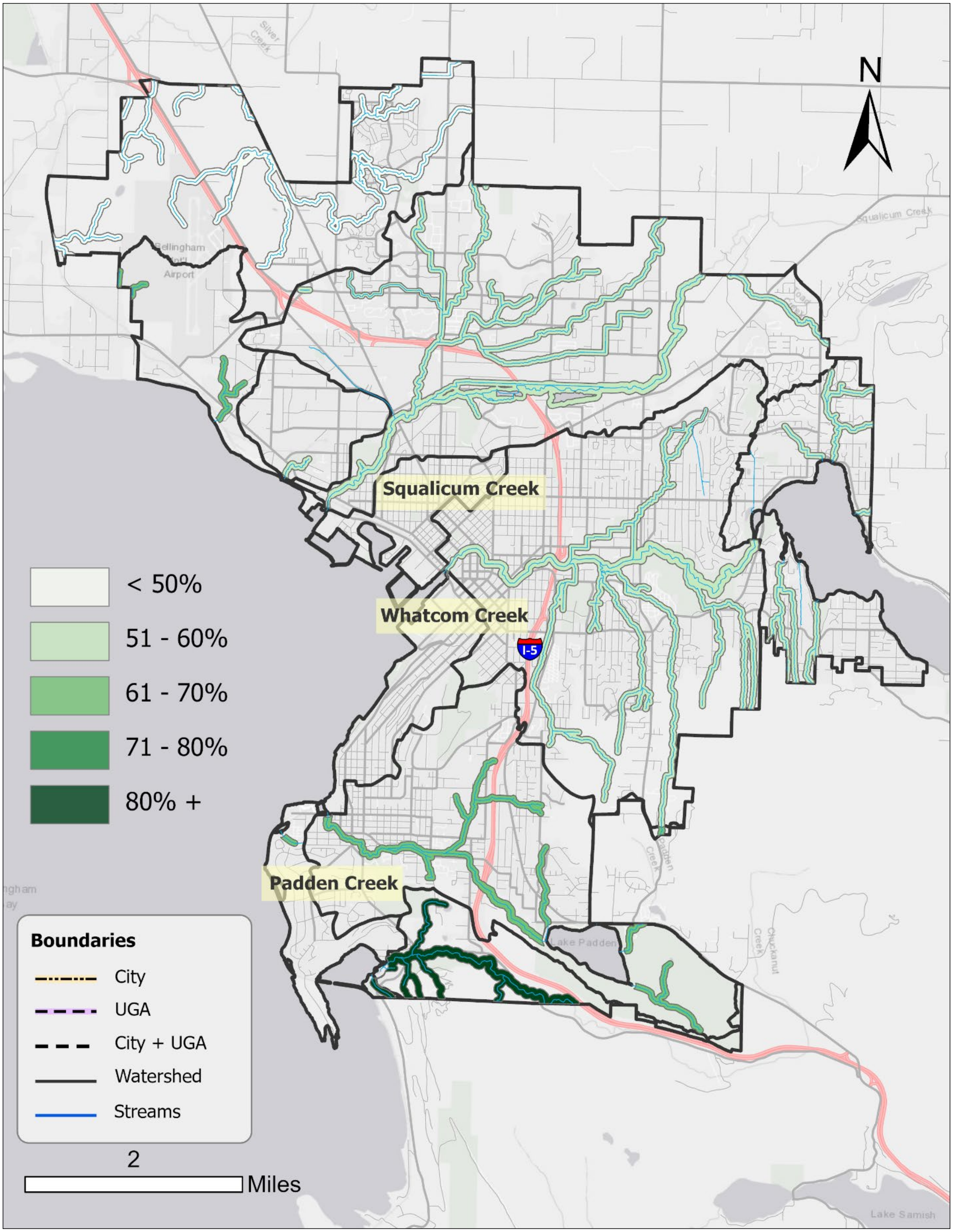

Figure 19. Canopy cover summarized by riparian areas within each watershed in 2018.

3.4 Forest Structure Analysis

The results of the forest structure analysis are mapped in Figure 19. The forest structure classes and their total area are summarized in Table 3.

Table 3. Forest structure classes.

Forest Structure Class	Approximate Height	Area (acres)
Old Forest	148 feet or more	91
Mature Forest	115 to <148 feet	492
Young Forest Tall	82 to <115 feet	2,543
Young Forest Short	33 to <82 feet	5,442
Pole Sapling Forest	10 to <33 feet	159
Shrub	<10	490

Core wood samples were taken at 16 representative ground sampling plots across the City to help verify tree ages within each successional stage. Young stands ranged in age from 23 to 80 and often contained scattered older trees with ages from 95 to 180. One sample was taken in a mature stand. The sample was not complete and the age was estimated as 145-155 years. Two samples were taken in stands classified as Old Forest with ages estimated at 150-170 and 130-150. It was found that in some forests there can be older trees mixed in with a younger generation of trees. This was the case where forests have been partially cleared or thinned in the past. In these cases, the stand was designated a successional stage that best reflects the more prominent canopy. Thirteen samples were taken from young forest stands.

Most forests were classified as young but many of these areas are at the point where they are transitioning between young and mature forest stages. Young forests have started to differentiate into distinct layers and this stage can begin as early as 20 years old in highly productive stands and can extend to approximately 80 years or more depending on when the stand structure becomes more complex.

Forest structure was distinctly different between the northern and southern portions of the city. The northern half of the city was dominated by young, mostly deciduous forest in structure classes Young Forest Short, Young Forest Tall, Pole Sapling and Shrub. The city's southern half was dominated by older, taller and more structurally-diverse forested stands in structure classes Young Forest Tall, Mature Forest, and even Old Forest.

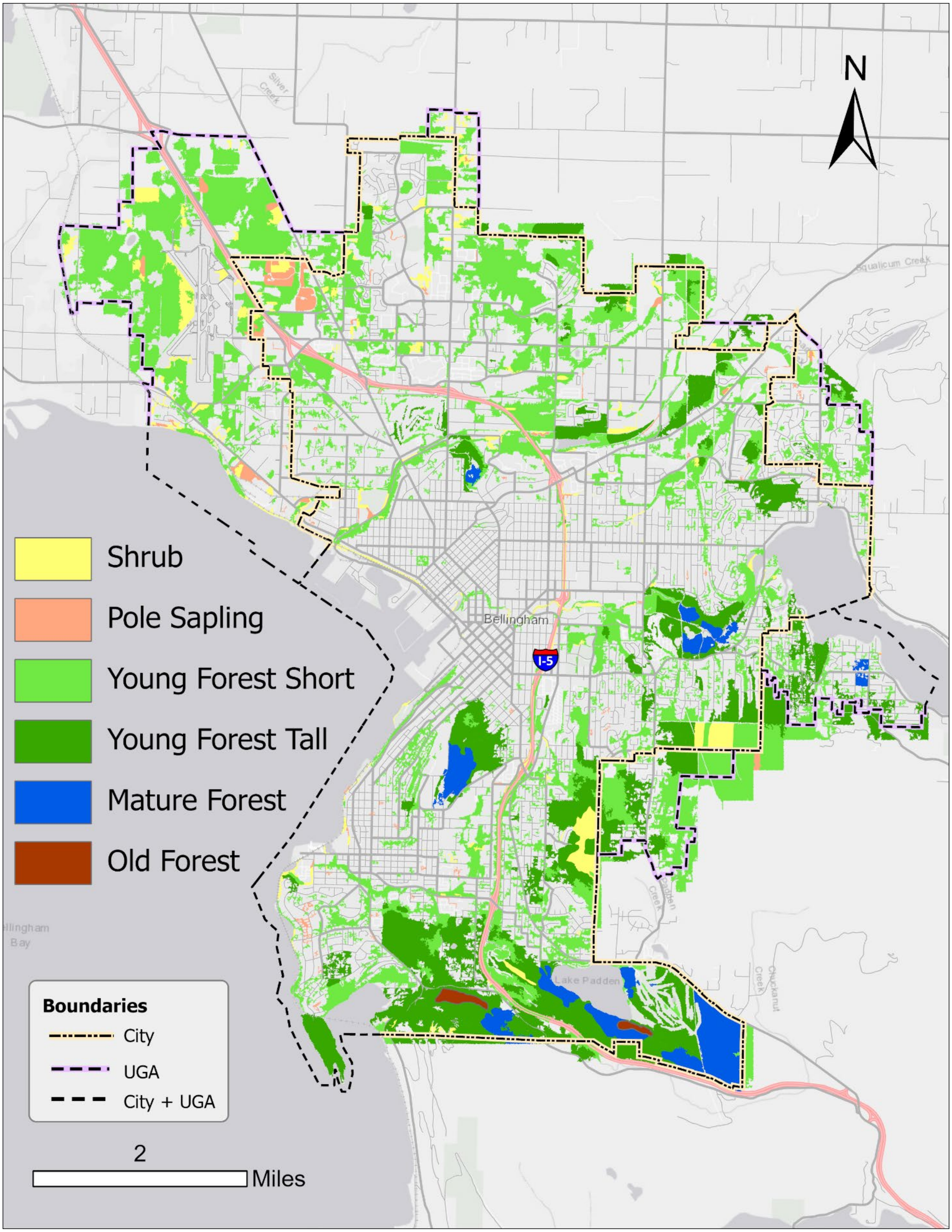

Figure 20. Forest structure classes derived from the 2013 LiDAR.

Figure 20 shows the canopy height model for Bellingham's forests. The tallest trees in the city were found in Mature Forest and Old Forest, with one Douglas-Fir measured at 251 feet from the LiDAR. Appendix 2 includes cross sections of each structure class visualized from the LiDAR point cloud.

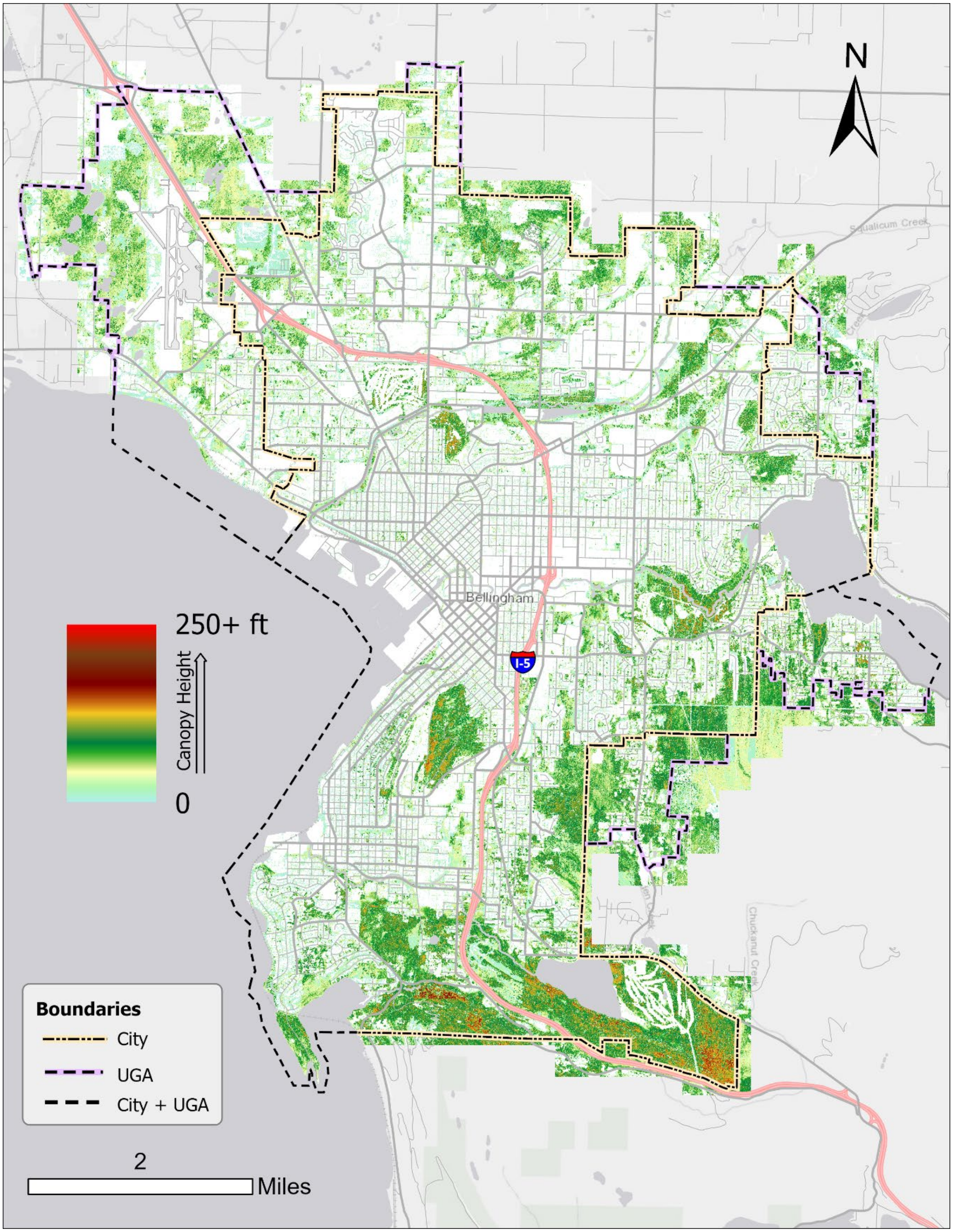

Figure 21. Canopy Height Model (CHM) and tallest tree location, derived from the 2013 LiDAR.

3.5 Forest Potential Analysis

3.5.1 Potential Forest Restoration Areas

Figure 21 identifies the immature forest (822 acres) and forest with the presence of noxious weeds that may impact tree growth (481 acres) throughout the City and UGA. With further review and refinement to incorporate local knowledge, these areas are anticipated to represent potential opportunities to restore forest cover and manage invasive species

3.5.2 Grass and Non-Vegetated Areas

Grass and non-vegetated areas that may have the potential to support tree planting in the future were identified throughout the City and UGA (Figure 21).

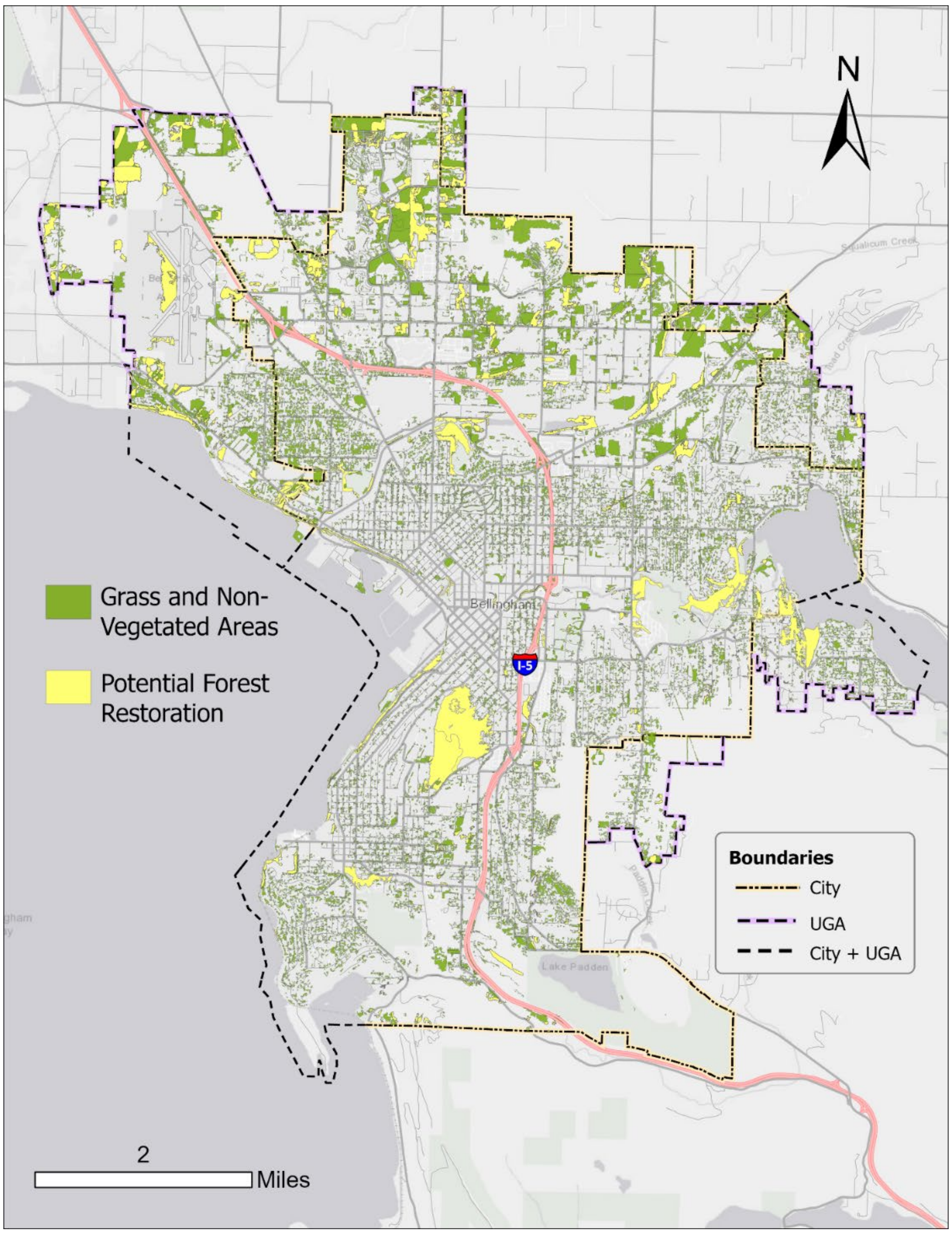

Figure 22. Forest Potential, does not account for constraints.

In an effort to understand the capacity of different areas to support additional forest cover, DHC estimated the number of trees that could occupy the grass and non-vegetated areas within the City and UGA if they were all forested. As discussed above, not all grass and non-vegetated areas can be converted to forest. Therefore the absolute numbers of trees and potential canopy area are a **significant overestimate**. However, these "raw" estimates provide an informative indication of the **relative proportion** of opportunities that are likely to exist by management unit. Absolute estimates of plantable areas and potential trees can be improved with further analysis. It is anticipated that private lands, right-of-way edges and other public lands have the greatest potential to support more canopy area.

The number of trees is based on the space required for each tree described in Section 2.3.2, above. The raw estimates of the number of trees that could potentially be planted in each summary zone are shown in Table 4.

Table 4. Raw estimate of potential trees by management unit based on conversion of all grass and non-vegetated land cover in Bellingham and UGA.

Summary zone	Raw* Estimate of Potential Trees by Zone	Percent of Total Potential Trees
City-Owned Special Use	120	0.1%
City-Owned-Community-Park	2,445	1.4%
City-Owned-Neighborhood Park	175	0.1%
City-Owned-Open-Space	1,100	0.7%
City-Owned-Other	1,350	0.8%
Other Public	13,150	7.8%
Private	129,270	76.6%
Rights-of-Way	21,100	12.5%
Citywide and UGA	168,710	100.0%

***Assumes all grass and non-vegetated areas converted to forest, does not account for constraints. Assumes that large trees would be planted preferentially over medium trees, which may not reflect reality; if small or medium trees were substituted then the total number of potential trees would be expected to increase.**

Figure 22 shows the raw estimate of potential trees converted into potential canopy area within the City and UGA. The graph shows that the most opportunity for tree planting and canopy gain likely exists in right-of-way, private land, and other public lands. This raw estimate of potential trees assumes **all** grass and non-vegetated areas could be converted to forested. As discussed above, in reality, not all grass and non-vegetated areas can be converted to forest. However, these coarse estimates provide an informative indication of the relative proportion of opportunities that are likely to exist by management unit. Absolute estimates of plantable areas and planting opportunities can be improved with further analysis.

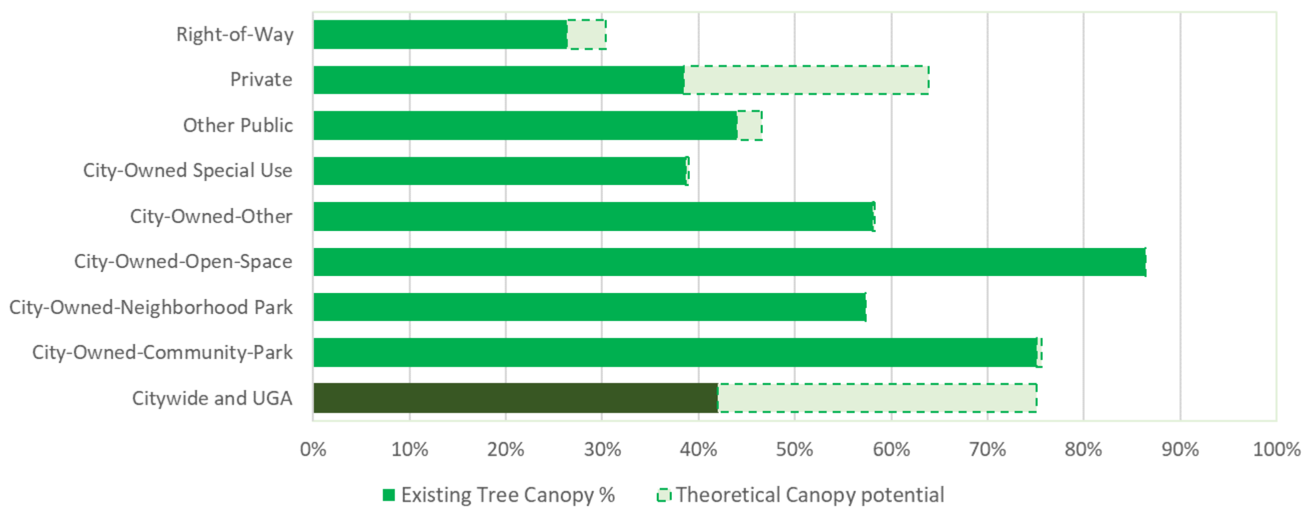

Figure 23. Canopy cover by management unit and theoretical canopy potential based on raw estimate of potential tree data (City and UGA), does not account for constraints.

Raw canopy potential on **private land** was assessed by neighborhood (Figure 26). The neighborhoods with the least potential for canopy expansion tended to be either very low canopy neighborhoods such as City Center (due to high impervious surface cover) or very high canopy neighborhoods such as Western Washington University (due to existing tree cover). The true canopy potential will be lower due to constraints on the ground, future development plans and competing needs but the graph shows the relative canopy potential by neighborhood. These results indicate that raising canopy cover in some low canopy cover neighborhoods is likely to require efforts to create new planting sites with redevelopment because of a lack of existing permeable areas for potential tree planting.

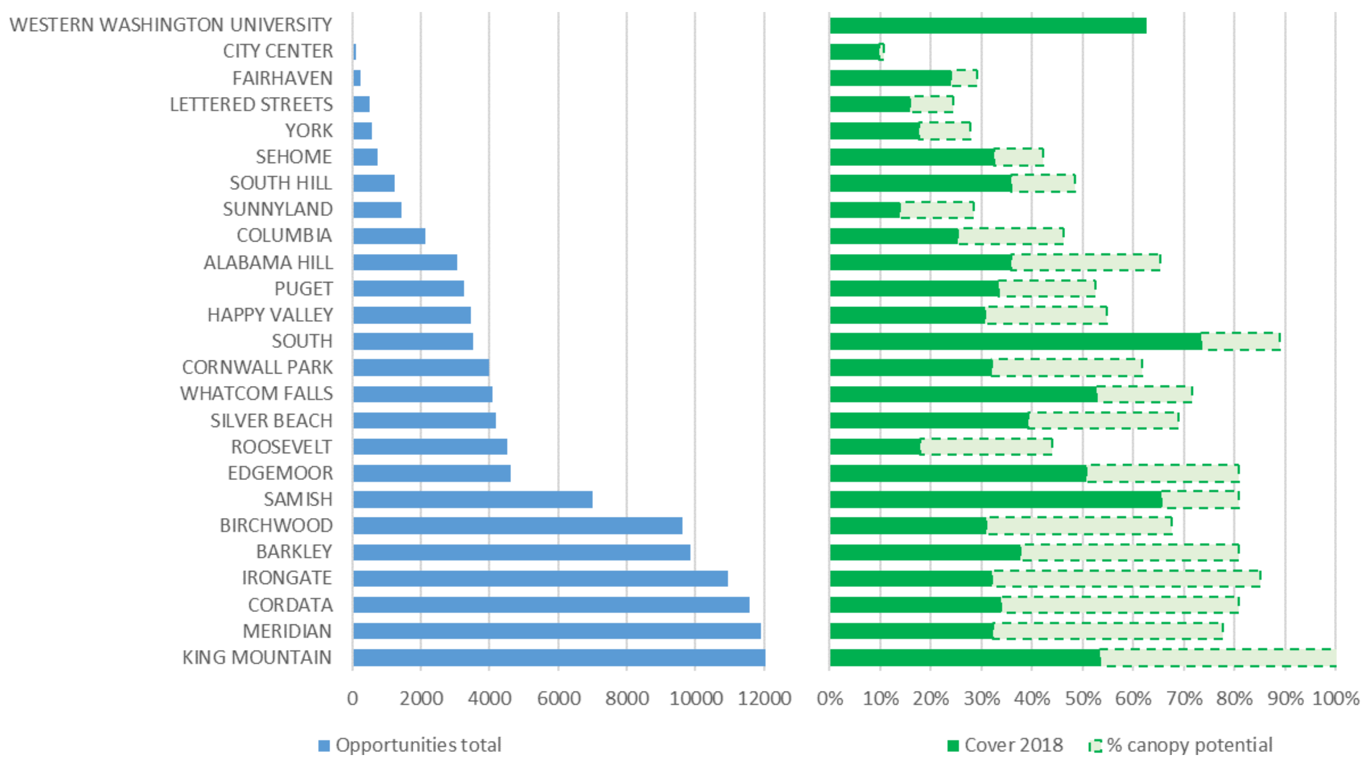

Figure 26. Raw potential canopy cover and theoretical canopy potential on private land by neighborhood (City only), does not account for constraints.

4.0 Summary of Key Findings

The key findings from the canopy and forest structure analysis tasks are that:

- Bellingham's canopy cover, including the Urban Growth Area, was 42% in 2018. The canopy cover within the City boundary was estimated at 40% canopy cover in 2018. Canopy cover has been relatively stable over the last 12 years.
- A slight gain in tree canopy was detected between 2006 and 2018, and most of the canopy was gained on private land and over roads.
- Canopy cover is not evenly distributed across Bellingham, with parks and undeveloped forest land, particularly near the edges of the City boundary, having disproportionately higher canopy cover.
- Canopy gain was observed from reforestation, new plantings in recently developed areas, and growth of existing trees and forests.
- Canopy loss was observed primarily due to forest harvesting and land clearing for development.
- Most of Bellingham's tree canopy is found on private land (54.3%), then on City-owned property (23.4%), other public lands (12.0 %) and rights-of-way (10.3%).
- Neighborhoods in the city's core have canopy cover well below the citywide average, with City Center having canopy cover of only 10%.
- The neighborhoods of Whatcom Falls and King Mountain were the only neighborhoods that showed a net loss of canopy cover between 2006 and 2018.
- Neighborhoods in the city's south have the highest canopy cover and the oldest forests.
- Sub-watershed canopy cover varied with Squalicum Harbor having the lowest canopy cover in the City at 14% and Chuckanut Creek having the highest canopy cover at 84%. The greatest canopy losses between 2006-2018 occurred in the Upper Spring Creek and Hannah Creek Sub-watersheds.
- Riparian areas in the city averaged 45% canopy or higher in 2018.
- The riparian zones within each watershed all exceeded 40% canopy cover. Canopy cover gains between 2006 and 2018 were observed for almost all riparian zones except Little Squalicum Creek, which declined, and Whatcom Creek, which remained stable. Riparian zones in Chuckanut Creek and Chuckanut Bay watersheds had canopy cover exceeding 80%.
- Most of the city's forests are young (50 years old or less) but large patches of mature and old forest are found in the southern portion of the City.
- Bellingham's tallest tree is estimated at 251 ft tall.
- Approximately 1,303 acres of existing forest has restoration potential within the City and UGA. This total consists of approximately 822 acres of immature forest based on being in shrub or pole sapling stage, or grass in riparian areas and approximately 481 acres of forest have potential invasive species issues that may impact tree growth.
- Significant potential exists for increased canopy coverage on private land and in rights-of-ways along roadside edges, and particularly in the Bellingham's northern neighborhoods.
- Few planting opportunities were identified on private land in the more central city neighborhoods that have the lowest canopy cover, suggesting that increasing canopy cover in these areas would require efforts to create new planting sites with redevelopment.

5.0 Next Steps

The findings outlined in this report will inform the next phases of developing Bellingham's Urban Forestry Management Plan. Phase 2 will engage the community to understand values, goals and objectives, and Phase 3 will involve developing the Plan. The next steps for developing Bellingham's Urban Forestry Management Plan will:

- Community values: This step consists of documenting community values, goals, and objectives for urban forest management to form the basis for future management decisions. This documentation will consist of gathering input from residents, interest groups, stakeholders, and City staff utilizing a 50- to 100-year planning horizon.
- Assess future development: Use the City of Bellingham's buildable lands assessment to estimate potential canopy losses on private land. Consider park and infrastructure plans and other guiding documents.
- Assess canopy expansion and forest restoration opportunities: Identify potential for canopy expansion and forest restoration by combining information on existing canopy, planting or restoration opportunities, existing forest structure, community goals, future development, and park/infrastructure plans.
- Establish canopy cover targets: Populate DHC's canopy forecasting model with existing canopy, opportunities assumptions and buildable lands assessment to develop canopy cover targets by management units.
- Review current practices: Review current practices, policies, and regulations to identify recommended changes.
- Create the plan: Prepare an Urban Forestry Management Plan that will serve as a strategic plan for articulating values, goals, and objectives. The Plan will summarize all prior forest analysis. The Plan will also describe recommended priority actions, strategies, staffing, resources, funding, and funding mechanisms for each strategy. Finally, the Plan will include measures and milestones to evaluate success.

6.0 References

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Appendix 1 - Canopy Layer Creation Steps

This appendix details the steps used to create the tree canopy polygon layers for 2006, 2013 and 2018:

1) nDSM (normalized Digital Surface Model)

The LiDAR point clouds were first normalized by extracting the height above the ground of each point. From these normalized point clouds, a 0.25-m normalized Digital Surface Model (nDSM) raster was derived providing the height above the ground of each pixel.

2) Segment Creation

The non-proprietary Random Forest algorithm (Breiman, Cutler, Liaw, & Wiener, 2018) was used to create vector segments because of its low bias, its ability to handle numerous predictor variables, its effectiveness in managing unbalanced data, and its general suitability for remote sensing applications. The algorithm's "special ingredients" are the input variables that are computed for the classification: a combination of spectral, textural and structural metrics that are used to distinguish between the various classes. The metrics were developed by researchers at the University of British Columbia and a third party consultant. Another ingredient is the training data, produced through visual interpretation of the imagery, which is a representative sample of each classes' spectral and textural variability.

The Random Forest object-oriented segmentation algorithm identified regions of image space that were more homogenous than neighboring regions and then built vector polygons around those regions (i.e. canopy, buildings, parking lots, cars, etc.). The capacity for the segmentation algorithms to delineate distinct surface features was enhanced by fusing the spectral and textural orthophoto information with the surface height information of the LiDAR raster nDSM for 2006 and 2013. For 2018, the spectral and textural information from the orthophoto was used in combination with 2013 LiDAR data. Three segment creation parameters were tested, and the best one chosen after reviewing several sample locations spread throughout the City.

3) Canopy Identification Classification

A Random Forest supervised machine learning classifier was applied to distinguish between canopy and non-canopy segments after it was trained on thousands of representative canopy/non canopy segment samples in Bellingham. The Random Forest machine learning classifier was especially adept at recognizing patterns in the imagery and then making predictions from those patterns over the entire study area. The canopy segments were then used to clip the LiDAR nDSM raster to produce a Canopy Height Model (CHM).

4) Tree Detection and Crown Delineation

For the automatic tree detection and crown delineation, a marker-controlled watershed algorithm, implemented in the ForestTools R library (Plowright & Roussel, 2021), was used to create individual vector canopy segments from the CHM. The peaks corresponding to the individual treetops were identified as local apexes, or markers. Using a moving window over the CHM, the vector polygons were created around each apex/marker using a watershed approach. The watershed simulates the immersion from markers to determine the flooded 'basins' (tree crowns in our case).

5) Coniferous/Deciduous Canopy Classification

After the creation of individual tree crown polygons, a final Random Forest classifier was applied to assign a coniferous or deciduous class to all detected trees. The classifier was trained on hundreds of known coniferous/deciduous tree samples from the City's street tree inventory and clear examples from the orthoimagery.

6) Segment Creation

To enable comparison of canopy segments through time, individual trees were matched between datasets. The data available for 2013 included both infrared imagery and a relatively dense point cloud LiDAR information, which provided the most accurate tree detection and tree classification results. The 2006 canopy mapping lacked infrared orthoimagery and so DHC "matched" tree canopy segments to 2013 whenever they overlapped. When multiple trees overlapped, DHC prioritized the tallest tree.

Matched trees inherited both the 'treeID' and 'crownClass' attribute from 2013. Unmatched trees were given a new unique 'treeID'. The matching process improved the 2006 deciduous/coniferous classification in the absence of infrared spectral information.

DHC ran the 2018 individual tree crowns through the same "matching" process that was applied for the 2006 baseline year: trees that overlapped with trees from 2013 had their 'treeID' and 'segClass' (deciduous or coniferous) copied over. Any other trees were given new treeID's, with a sequence starting at 2,000,000 so that they would not match any of the IDs from 2006.

7) Manual Editing

The editing/clean-up workflow entailed photointerpretation using the orthoimagery, LiDAR nDSM rasters and, occasionally, Google Street View. In some instances, canopy polygons from 2013 were also used to better contextualize the 2006 canopy.

Our manual review team inspected the crown polygons block by block and removed artifacts like building roofs, shadows, and non-tree objects that were mistakenly captured by the segmentation algorithm. The 'Edited' field identifies any tree polygon that had a portion removed/cut-out.

- The most common classification errors are identified in Figure 23:
    - Power lines (when they are interspersed with crowded areas of forest)
    - Light poles/cars
    - High building edges nearby trees
    - Part of a waterbody (due to organic matter on the water surface)
    - Hedges under 3m
    - Trees nearby areas like ports or bridges

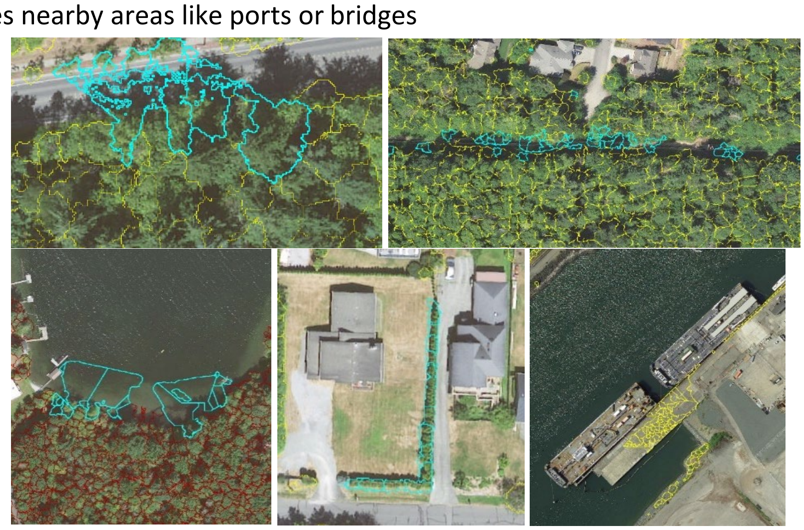

Figure 24. Examples of the most common classification errors. Canopy extension near roads (top left), power lines through dense forest (top right), nearby water bodies (bottom left), short hedges (bottom middle), and near port lands (bottom right).

Significant manual editing was conducted by DHC's manual review team to eliminate artifacts from the 2018 canopy file. Due to the temporal mismatch in the datasets, significant artifacts had to be removed. The "Edited" field again identifies canopy polygons that had been modified. While the dataset effectively captures loss from 2013, gain is harder to identify due to a lack of up-to-date 3D height information. Finally, any polygons smaller than 21 ft^2 or shorter than 3 ft were deleted, consistent with the methodology from 2006 and 2013.

Due to the five-year temporal mismatch between the 2018 orthophoto and 2013 LiDAR datasets, a classification step was added to target areas of large-scale tree removal in the 2018 mapping. The areas of large-scale tree removal were identified through the Landsat-based data on yearly forest loss data provided by the University of Maryland's Department of Geographical Sciences (Hansen, et al., 2013). This extra step was added to ensure that trees visibly absent in the 2018 orthoimagery but present in the 2013 LiDAR data were excluded from the 2018 canopy mapping.

After manual editing, the zonal statistics tool was run in ESRI's ArcGIS Pro software to assign a height min, max, average, and standard deviation to every tree polygon based on the nDSM raster. Any polygons with an average height shorter than 3 ft were deleted in a mass update across the city. Any polygons smaller than 21 ft^2 were also deleted.

8) Accuracy Assessment

DHC conducted an accuracy assessment on a random selection of 500 trees from the edited 2013 canopy polygon feature class. The random sample of trees was cross-referenced with the nDSM/2013 ortho/Google Street View imagery (in and around 2013) to determine if a tree is present or absent. A confusion matrix was subsequently created for both tree presence/absence and crown deciduous/ coniferous classification results. The accuracy assessment found that the canopy mapping is accurate at representing trees (False Positive rate of 1%) and their associated deciduous/coniferous crown classes (False Positive/Negative rate of 4%).

Table 5. Confusion matrix for tree presence/absence

	Predicted	
Actual	Presences	Absences
Presences	496	N/A
Absences	4	N/A
Total	**500**	

Classification accuracy based on the confusion matrix for presence (presence is considered as positive; absence is considered as negative):

- **True Positives (TP)**—the correctly detected trees: 496, TP rate of 99%
- **False Positive (FP)**—the number of trees incorrectly detected by the algorithm at locations where no trees are present: 4, FP rate of 1%

Table 6. Confusion matrix for coniferous/deciduous

	Predicted		
Actual	Presences	Absences	**Total**
Presences	214	10	324
Absences	9	267	276

Total	223	277	500

Classification accuracy based on the confusion matrix for crown class (Coniferous is considered as positive; Deciduous is considered as negative):

- **True Positive (TP):** 214/223 = 96%
- **False Positive (FP):** 9/223 = 4%
- **True Negative (TN):** 267/277 = 96%
- **False Negative (FN):** 10/277 = 4%

No formal accuracy assessment was performed on the 2018 or 2006 datasets. However, significant manual review/editing was performed on these datasets on a block-by-block basis by a four-person GIS team in order to ensure consistency with the 2013 canopy mapping. In addition, the US Department of Agriculture's i-Tree Canopy program (i-Tree Software Suite v.7.1, n.d.) was used to estimate canopy cover over the 2018 orthophoto as a verification step. The i-Tree Canopy results (see next page) agreed with the 2018 canopy mapping results.

Canopy Layer References

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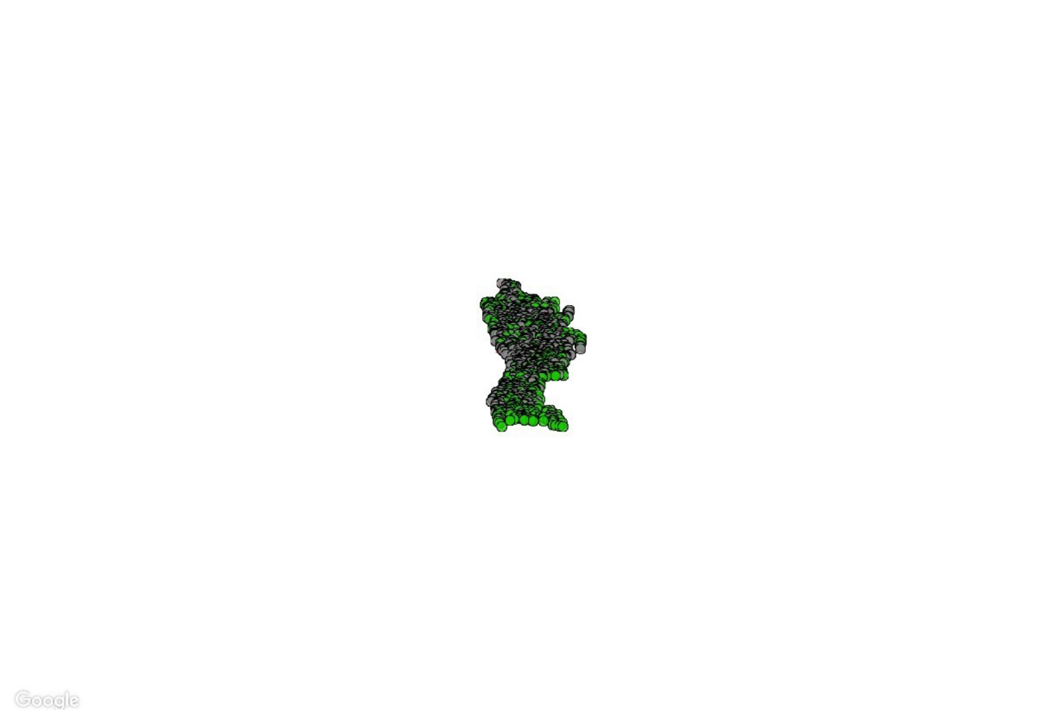
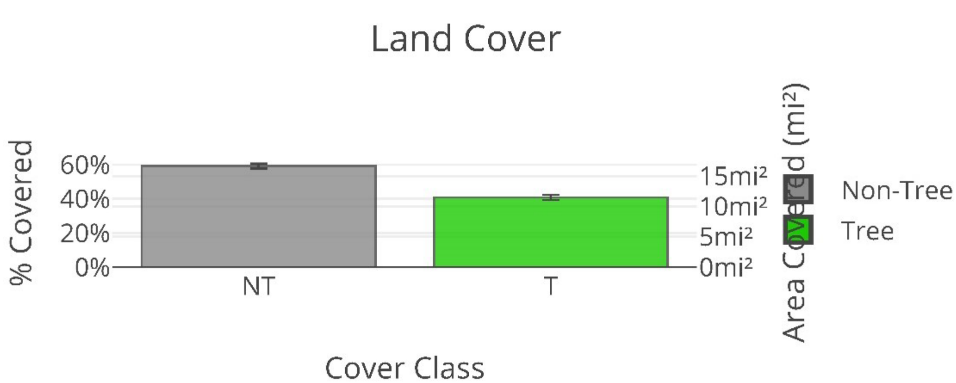
i-Tree Canopy Results

i-Tree Canopy v7.1

Cover Assessment and Tree Benefits Report

Estimated using random sampling statistics on 2/25/2021





Abbr.	Cover Class	Description	Points	% Cover ± SE	Area (mi^2) ± SE
NT	Non-Tree	All other surfaces	646	59.16 ± 1.49	16.63 ± 0.42
T	Tree	Tree, non-shrub	446	40.84 ± 1.49	11.48 ± 0.42
Total			**1092**	**100.00**	**28.11**

Tree Benefit Estimates: Carbon (English units)

Description	Carbon (kT)	±SE	CO_2 Equiv. (kT)	±SE	Value (USD)	±SE
Sequestered annually in trees	8.46	±0.31	31.01	±1.13	$1,442,304	±52,528
Stored in trees (Note: this benefit is not an annual rate)	251.89	±9.17	923.61	±33.64	$42,960,585	±1,564,616

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Amount sequestered is based on 0.737 kT of Carbon, or 2.701 kT of CO_2, per mi^2/yr and rounded. Amount stored is based on 21.940 kT of Carbon, or 80.446 kT of CO_2, per mi^2 and rounded. Value (USD) is based on $170,550.73/kT of Carbon, or $46,513.84/kT of CO_2 and rounded. (English units: kT = kilotons (1,000 tons), mi^2 = square miles)

Tree Benefit Estimates: Air Pollution (English units)

Abbr.	Description	Amount (T)	±SE	Value (USD)	±SE
CO	Carbon Monoxide removed annually	2.55	±0.09	$3,400	±124
NO2	Nitrogen Dioxide removed annually	25.81	±0.94	$7,079	±258
O3	Ozone removed annually	182.58	±6.65	$491,035	±17,883
SO2	Sulfur Dioxide removed annually	9.89	±0.36	$1,078	±39
PM2.5	Particulate Matter less than 2.5 microns removed annually	14.08	±0.51	$2,163,022	±78,777
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	53.91	±1.96	$337,962	±12,308
Total		**288.81**	**±10.52**	**$3,003,575**	**±109,390**

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Air Pollution Estimates are based on these values in T/mi^2/yr @ $/T/yr and rounded:

CO 0.222 @ $1,333.50 | NO2 2.248 @ $274.26 | O3 15.902 @ $2,689.49 | SO2 0.861 @ $109.05 | PM2.5 1.226 @ $153,641.62 | PM10* 4.696 @ $6,268.44 (English units: T = tons (2,000 pounds), mi^2 = square miles)

Tree Benefit Estimates: Hydrological (English units)

Abbr.	Benefit	Amount (Mgal)	±SE	Value (USD)	±SE
AVRO	Avoided Runoff	218.79	±7.97	$1,955,131	±71,205
E	Evaporation	1,024.76	±37.32	N/A	N/A
I	Interception	1,029.40	±37.49	N/A	N/A
T	Transpiration	472.54	±17.21	N/A	N/A
PE	Potential Evaporation	3,074.33	±111.97	N/A	N/A
PET	Potential Evapotranspiration	2,613.46	±95.18	N/A	N/A

Currency is in USD and rounded. Standard errors of removal and benefit amounts are based on standard errors of sampled and classified points. Hydrological Estimates are based on these values in Mgal/mi^2/yr @ $/Mgal/yr and rounded:

AVRO 19.057 @ $8,936.00 | E 89.257 @ N/A | I 89.660 @ N/A | T 41.158 @ N/A | PE 267.774 @ N/A | PET 227.632 @ N/A (English units: Mgal = millions of gallons, mi^2 = square miles)

About i-Tree Canopy

The concept and prototype of this program were developed by David J. Nowak, Jeffery T. Walton, and Eric J. Greenfield (USDA Forest Service). The current version of this program was developed and adapted to i-Tree by David Ellingsworth, Mike Binkley, and Scott Maco (The Davey Tree Expert Company)

Limitations of i-Tree Canopy

The accuracy of the analysis depends upon the ability of the user to correctly classify each point into its correct class. As the number of points increase, the precision of the estimate will increase as the standard error of the estimate will decrease. If too few points are classified, the standard error will be too high to have any real certainty of the estimate.

Additional support provided by:

Use of this tool indicates acceptance of the EULA.

Appendix 2 – Forest Structure Methodology and LiDAR Cross Sections

This appendix describes the methodology used to create the forest structure layer, and presents cross- section of each forest structure class.

LiDAR forest metrics

The first step in the forest structure analysis was to create the forest height metrics as raster datasets. First, all overlapping returns in the 2013 Lidar dataset were flagged and removed from any subsequent analysis. Next the 'LAS Height Metrics' tool was run in ESRI's ArcGIS Pro 3D Analyst extension using all vegetation returns above 3 feet in height. The minimum number of LiDAR points to be considered in the calculation was 3 per raster cell, and the raster cell size was 9.84 feet (3 meters). The LAS height metrics tool generates mean, standard deviation, skewness, kurtosis, mean absolute deviation, as well as 10, 15, 20, 25, 50, 80, 85, 90, 95 height percentiles as continuous raster surfaces for the entire City. The resulting rasters were important ancillary pieces of information in classifying the forest structure stands that were derived in the next steps.

Forest structure polygons

The following detailed steps were taken to derive the forest structure vector dataset:

- Run a dissolve on the 2013 canopy layer based on species composition (coniferous/deciduous)
- Run a topology clean/polygon clean up tool on the resulting layer
- In the QGIS software, run a simplify polygon tool with a 3 feet maximum offset tolerance to generalize the polygons and make the subsequent steps less computationally-intensive
- Visually inspect the result, then, in QGIS, run a fill gap function to fill any gaps within the generalized polygons that are smaller than 10,000 ft^2
- Using ET Geowizards, run a clean gap function to identify any 'sliver' gaps that exist between the polygons
- Visually inspect the result, then delete any resulting 'gap' polygons that have an area over 30,000 ft^2 (larger water ponds, large open areas with grass within forest patches, etc)
- Run the eliminate tool in QGIS to integrate all gap polygons smaller than 30,000 ft^2 into the adjacent forest polygons based on the largest shared common boundary option
- Run the eliminate tool to integrate all forest polygons smaller than 5 acres into the adjacent forest polygon based on the largest area option
- Manually edit the resulting layer and incorporate smaller forest stands that are on the boundary of larger forest stands which were not picked up by the eliminate processes in the previous steps.

- Manually edit the resulting layer and amalgamate smaller adjacent forest stands that individually are not over 5 acres, but collectively meet the size requirement when merged.
- Delete all the remaining polygons under 0.25 acres (~0.1 Ha). Retain the polygons over this size threshold that might not be important forest stands from a city-wide structure perspective, but are important pieces from a forest connectivity/habitat analysis standpoint

Forest structure polygon refinement

- Take a look at the larger, amalgamated forest stand polygons and, using the LiDAR rasters derived in step 1 alongside the 2013 canopy layer, make cuts where there are major differences in:
  - 95th percentile height values
  - skewness
  - standard deviation
  - coniferous/deciduous composition
- First, look at 95 percentile height for each plot to classify: (1) old growth stands (40m+), (2) mature stands (35m – 40m), and (3) young/pole sapling stands (10 – 35m)
- DHC conducted research on forest stand structural characteristics based on LiDAR height metric rasters. The summary of research indicated that mature stands have a high negative skewness and young stands have a positive skewness
  - -0.5 to 0.5: fairly symmetrical
  - -1 to -0.5 or 0.5 to 1: moderately skewed
  - Less than -1 or greater than 1: highly skewed (old growth forests have highly negative skewness values, but mature/young forests do have negative skewness values down to -3).
- With respect to forest strata, take a look at the standard deviation and the direction of skewness to identify if there's multiple strata present.
  - Higher std. => uneven-aged structure
  - Lower std. => even-aged structure
- Based on the observed forest strata characteristics of the numerous ground-truth plots collected in the field, the following cut-off values were utilized to consider forest strata:
  - Single-storied: std. ≤ 12 ft.
  - Two-storied: 12 ft. < std. ≤ 32 ft.
  - Multi-storied: std. ≥ 32 ft.
- All of the above steps were supplemented by 2013 and 2018 orthophoto analysis, ground plot information, historical aerial imagery, and City comments

Forest structure polygon metrics

- Run a spatial join with the 2013 canopy centroid points to identify the percentages of deciduous and coniferous trees that each refined forest structure polygon contains. If a forest structure polygon contains greater than 70% coniferous or deciduous trees, it was noted as such, and if the percentage was less than 70%, it was designated as mixed.
- The spatial join also generated summary statistics for height and crown area metrics for each forest structure polygon. The height classes of 1-4 were derived from these summary statistics.

Clean-up and final verification

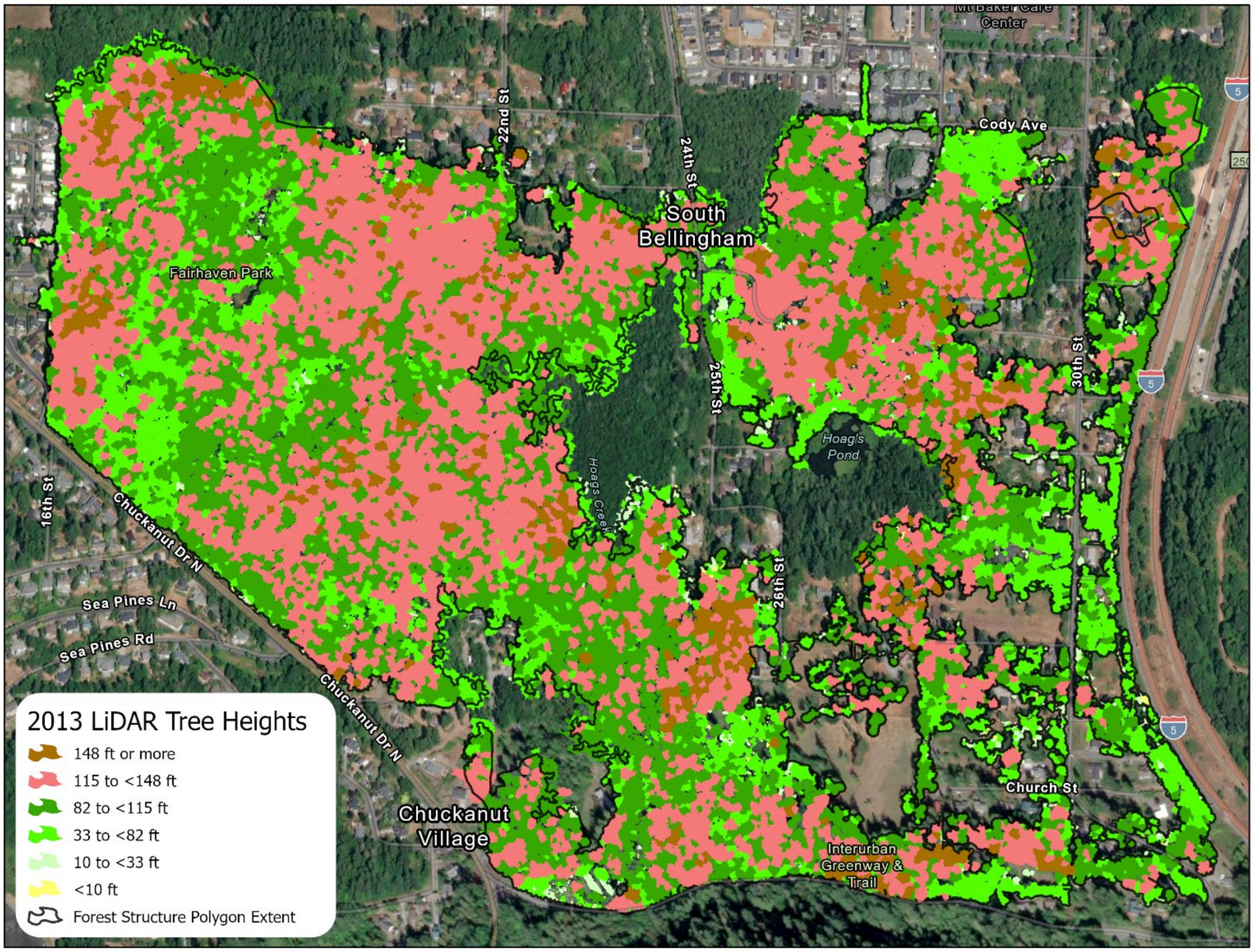
- Manually edit the forest structure polygons to remove areas where the forest has been cleared/cut/removed since 2013 (using the 2018 ortho, and in some cases, 2019 leaf-off ortho).
- Manually edit this layer to add in areas that are occupied by shrubs. Use the 2018 canopy layer and 2018 ortho to add in missing shrub areas
- Use the City's various wetland layers to add in areas that are occupied by significant wetland habitat
- Use the 18 ground plots collected in August of 2020, as well as the ground plots collected in March of 2021 to perform a final check of forest structure stand characteristics

Forest health

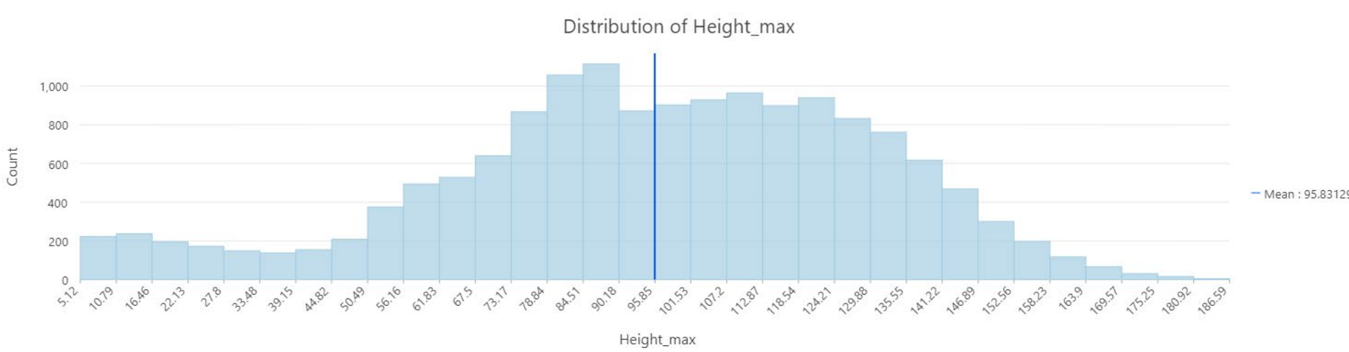
- Intersect the WADNR aerial survey polygons from the year 2010 onwards with the forest structure polygons to identify areas with health concerns. Supplement this information with ground truth data already collected and COB comments.

Lidar Height Averages

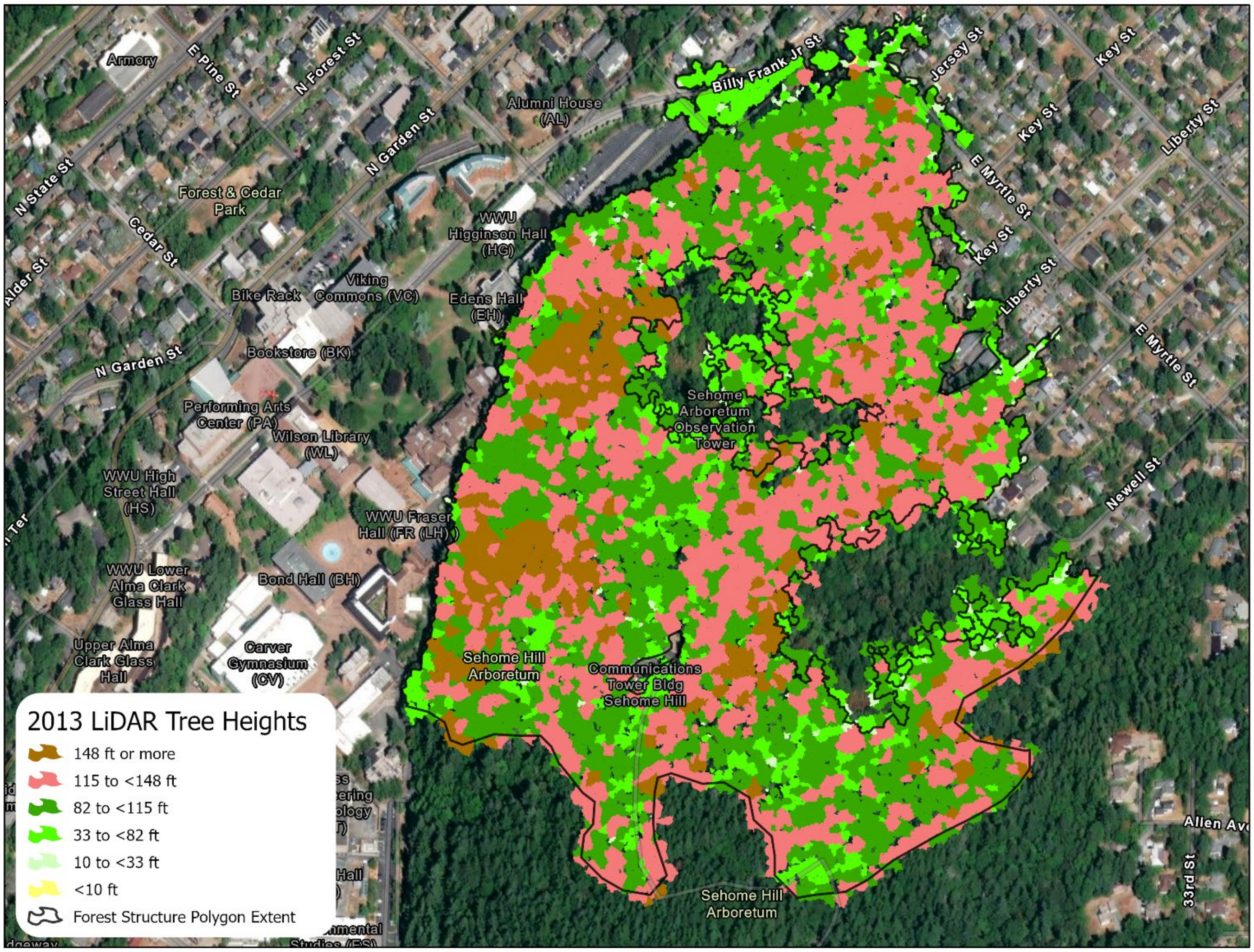
LiDAR provides accurate heights of all trees in these stands. The averages reported for each forest structure polygon accounts for all the trees at all canopy levels and averages heights across the entire polygon. Figures below illustrate tree heights and height distribution graphs for forest structure polygons in the Chuckanut Community Forest, northern Sehome, southern Sehome, Whatcom Creek, and Whatcom Falls.



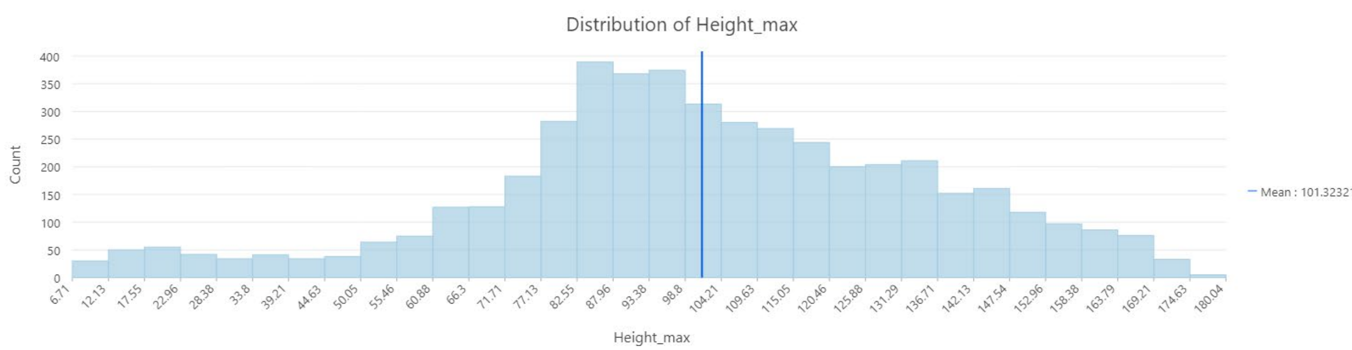
South Bellingham forest structure polygon, inclusive of the Chuckanut Community Forest



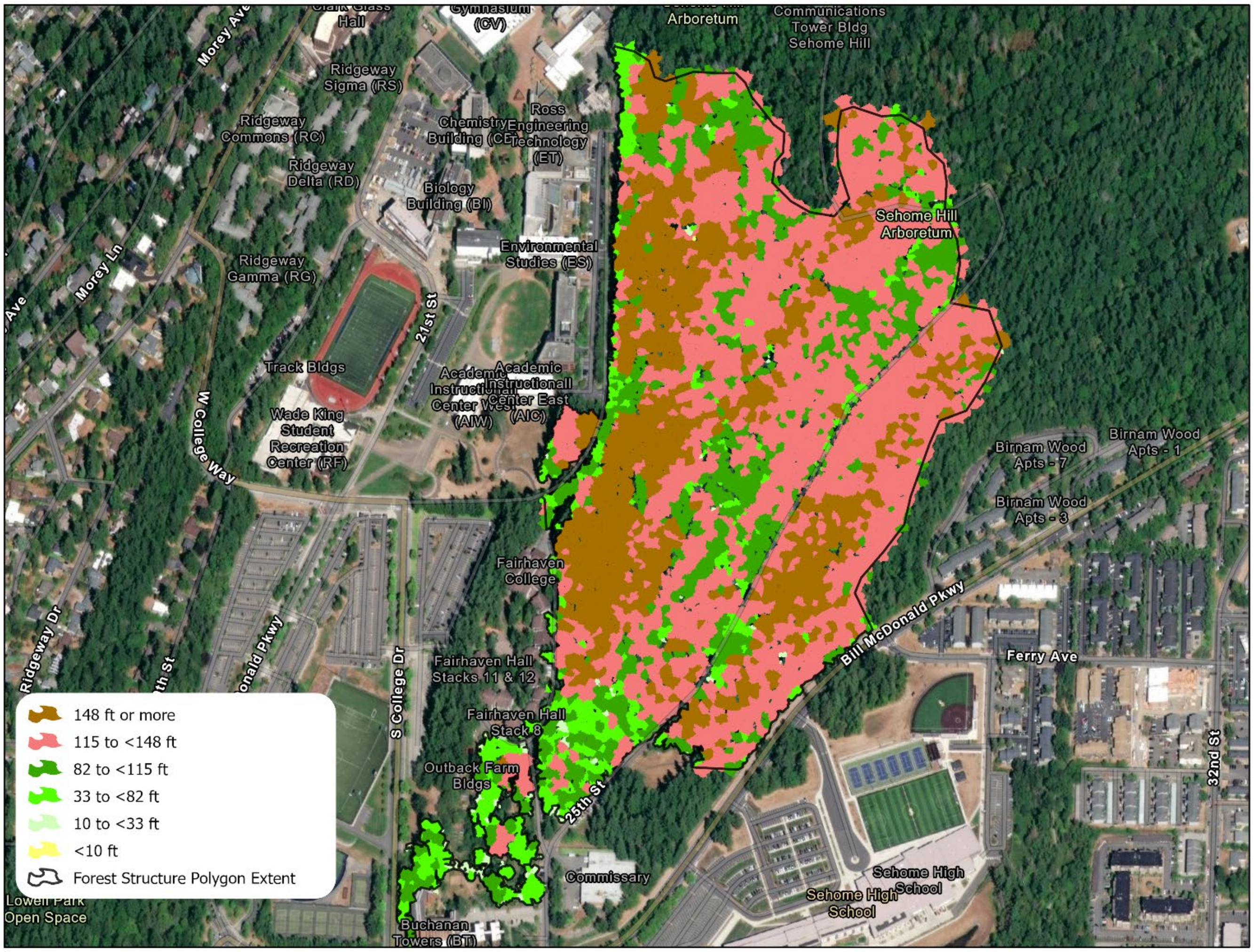
South Bellingham forest structure polygon LiDAR tree height distribution



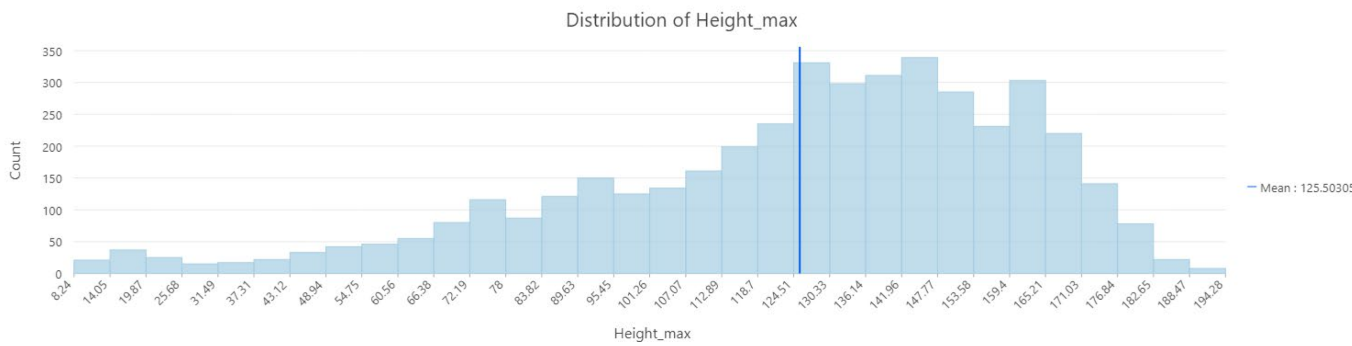
Northern Sehome forest structure polygon



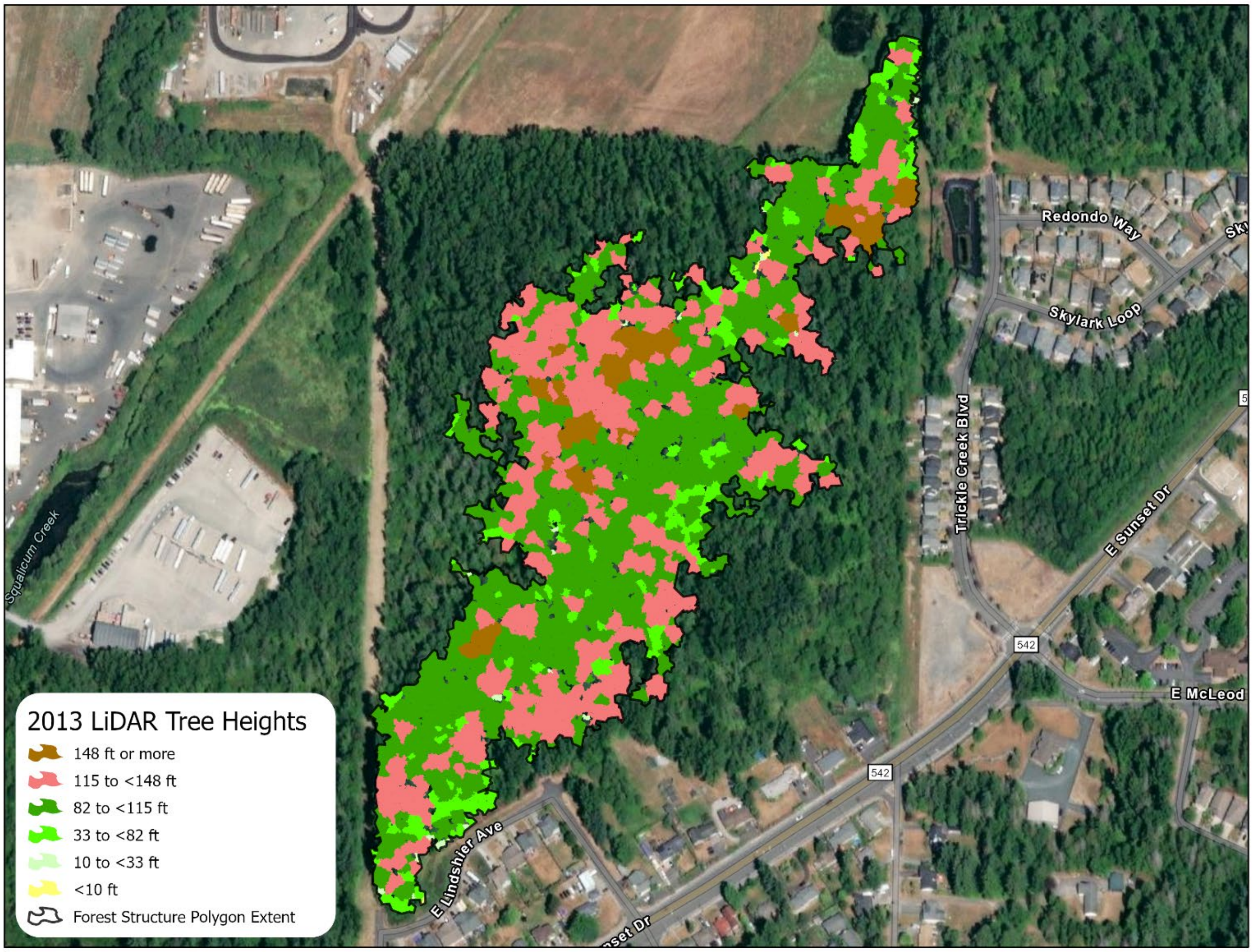
Northern Sehome forest structure polygon LiDAR tree height distribution



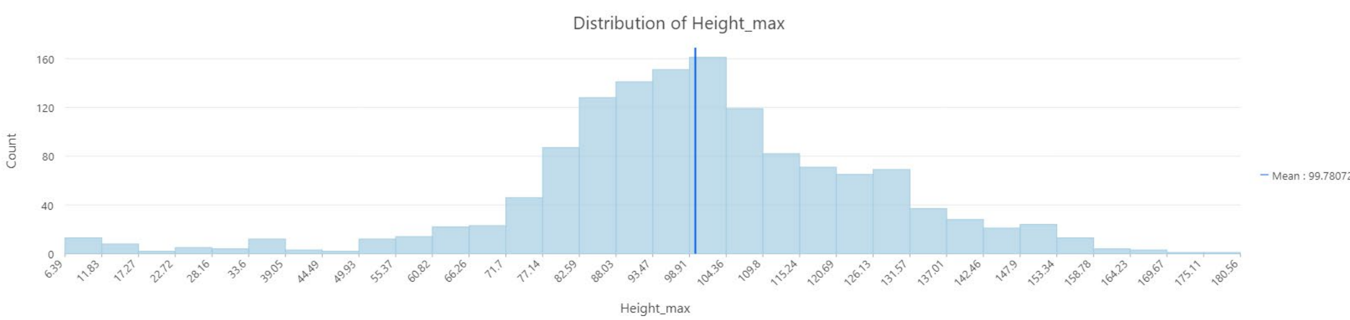
Southern Sehome forest structure polygon



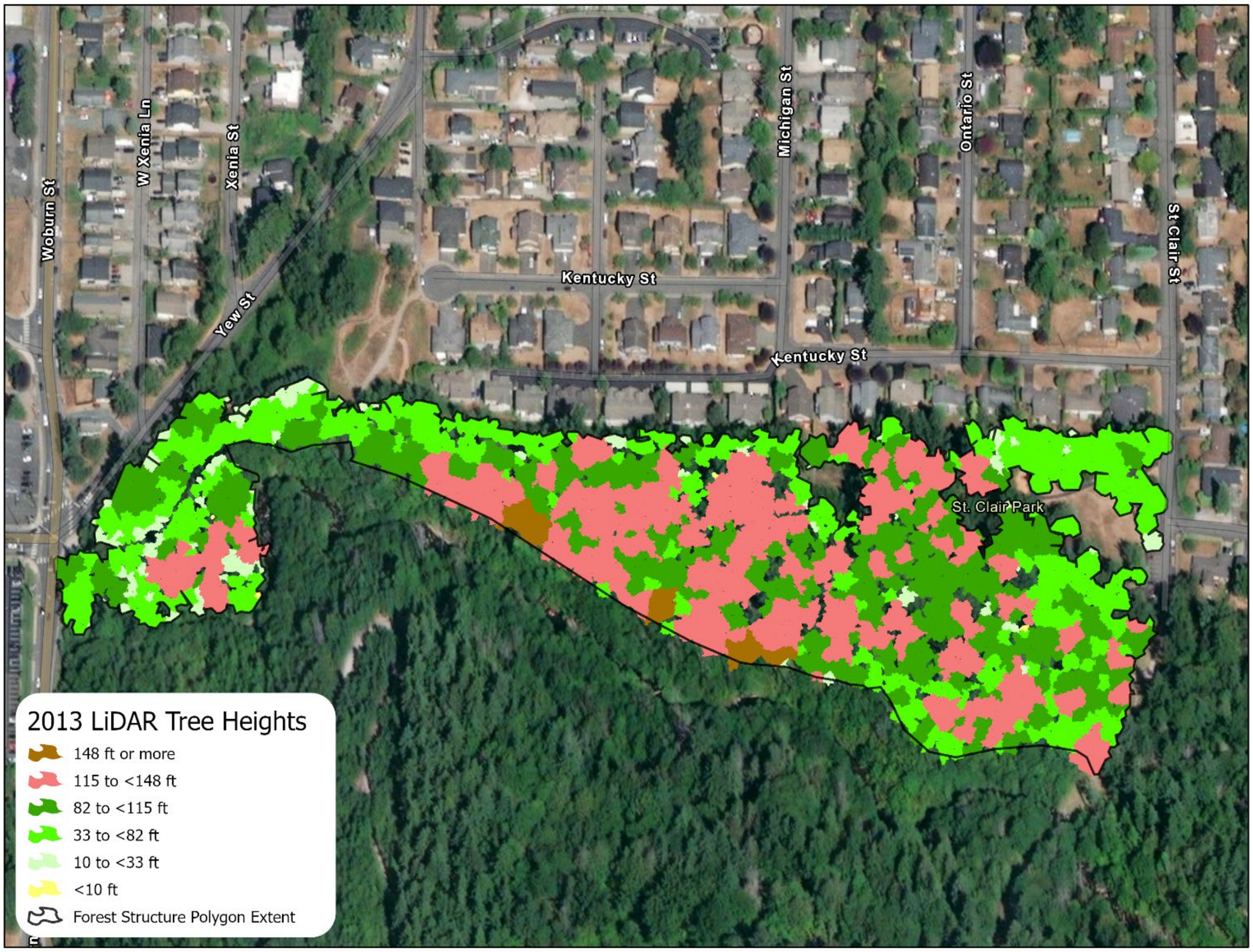
Southern Sehome forest structure polygon LiDAR tree height distribution



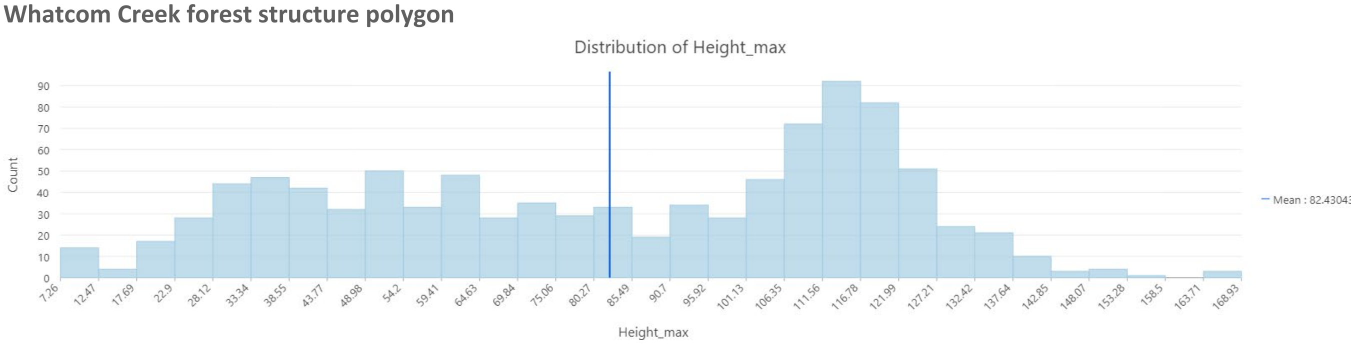
Sunset Drive forest structure polygon



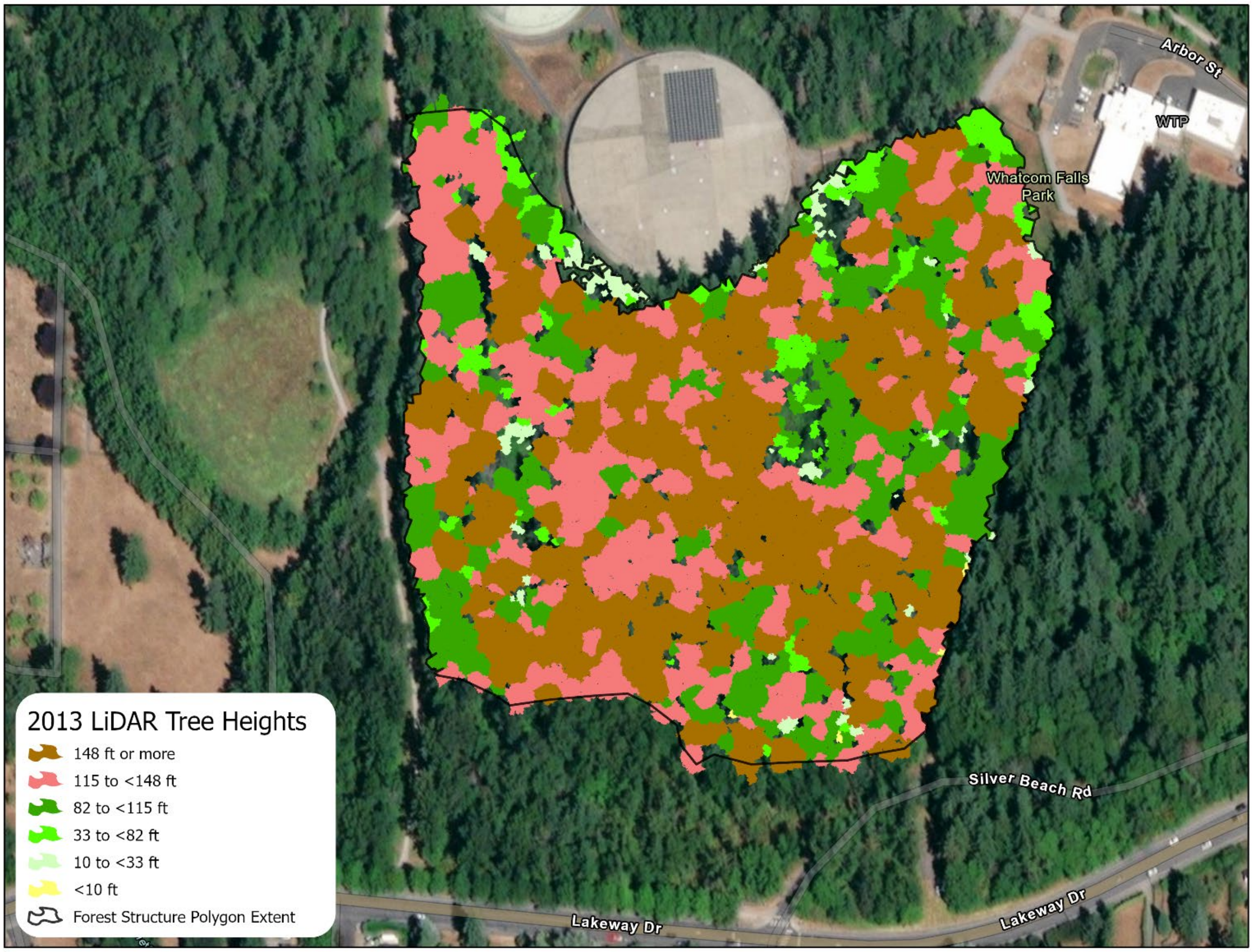
Sunset Drive forest structure polygon LiDAR tree height distribution



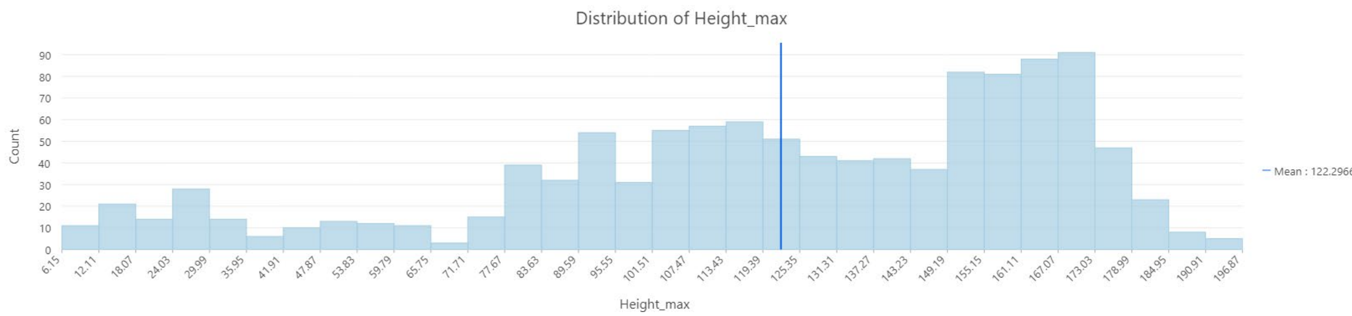
Whatcom Creek forest structure polygon



Whatcom Creek forest structure polygon LiDAR tree height distribution

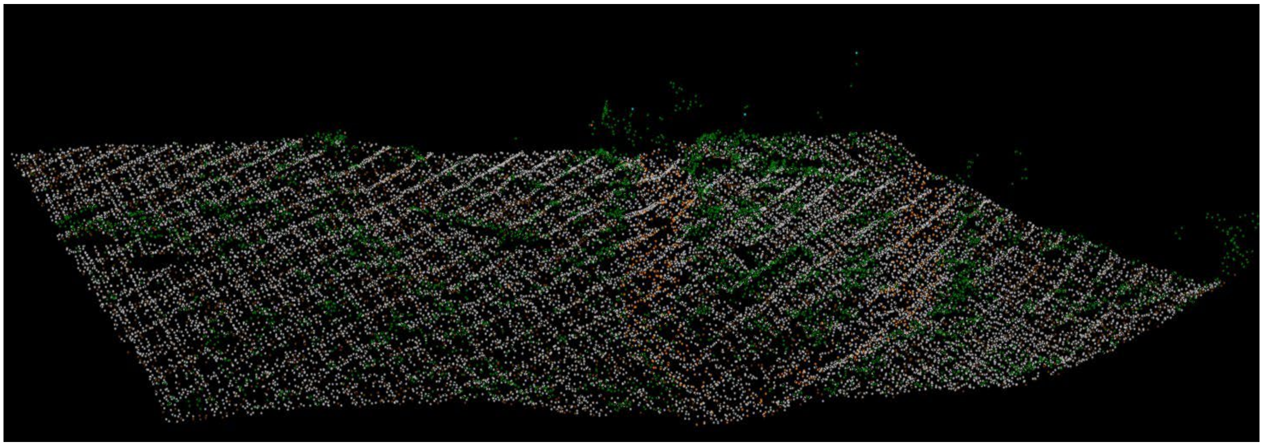


Whatcom Falls forest structure polygon



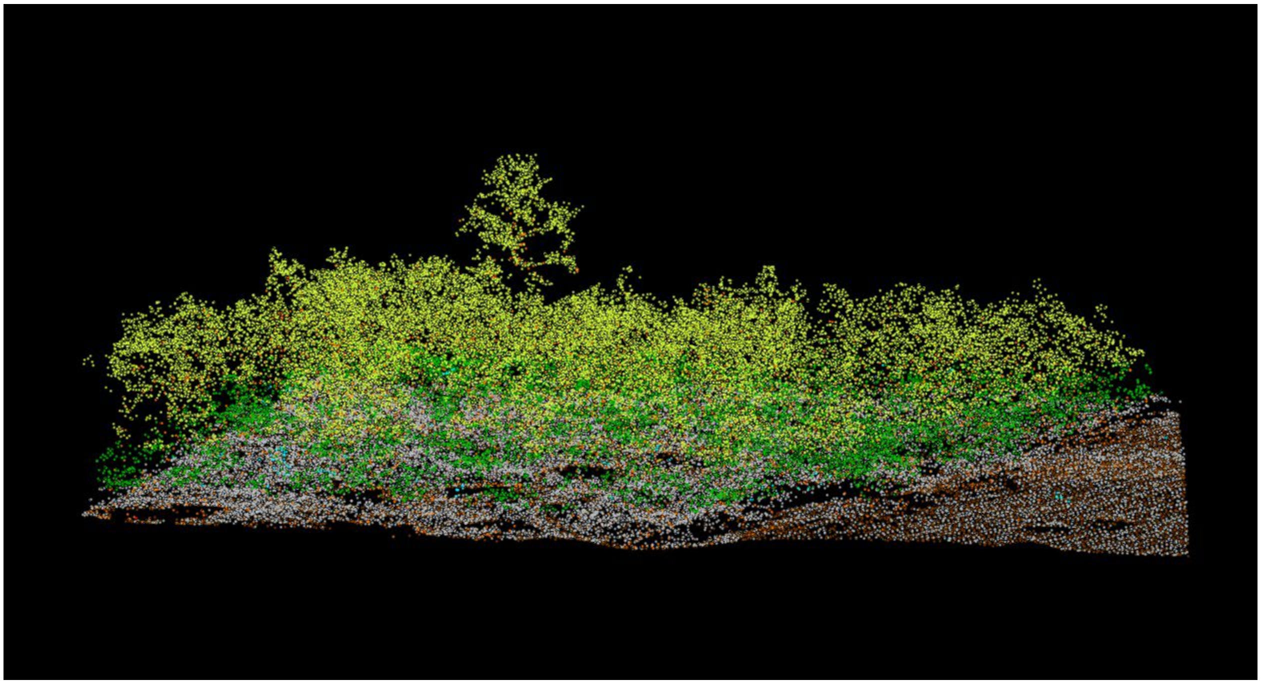
Whatcom Falls forest structure polygon LiDAR tree height distribution

Lidar Cross Sections

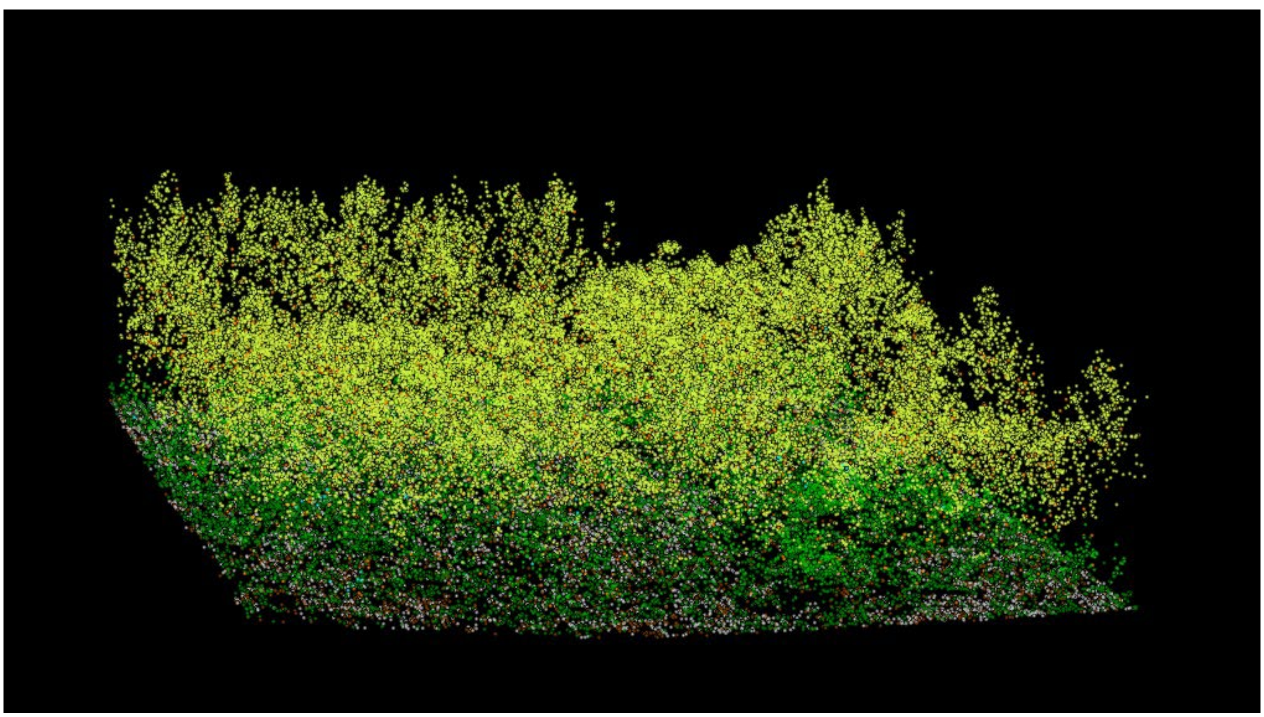


Shrub cross section (deciduous), with few low vegetation returns displayed

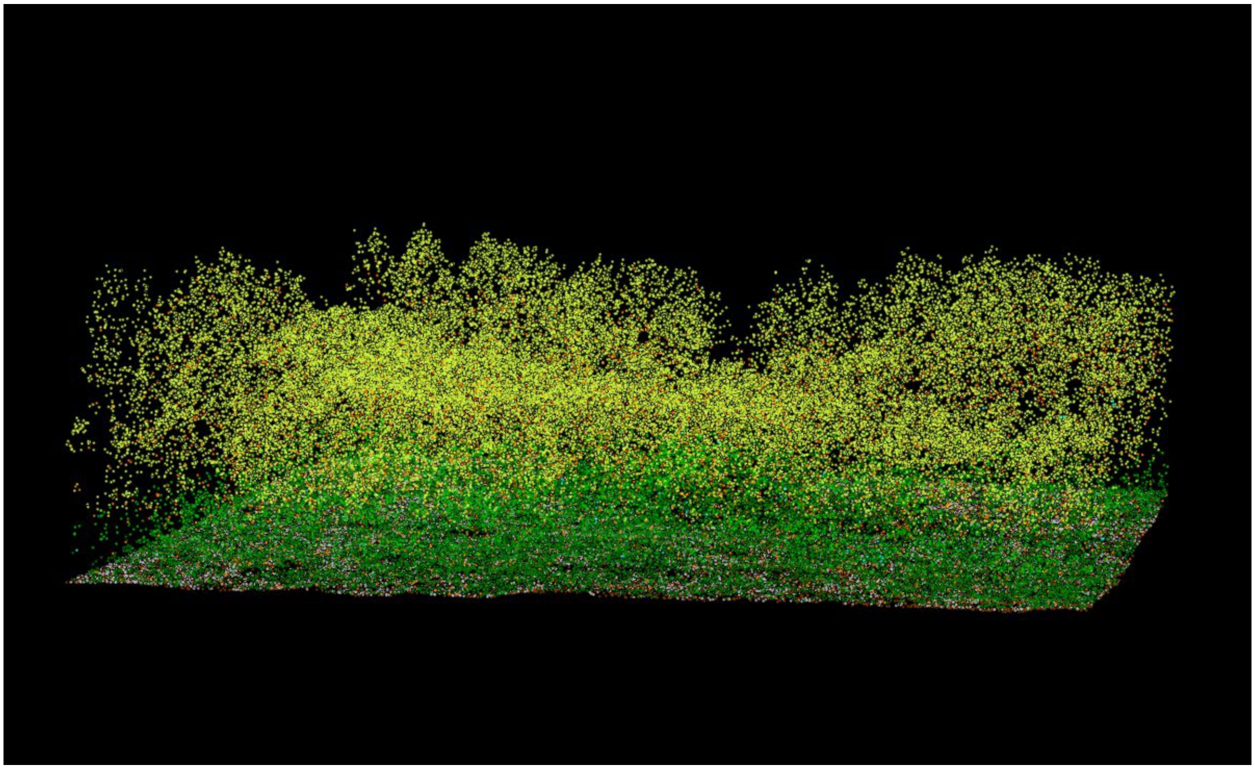
Pole sapling (deciduous) cross section 1



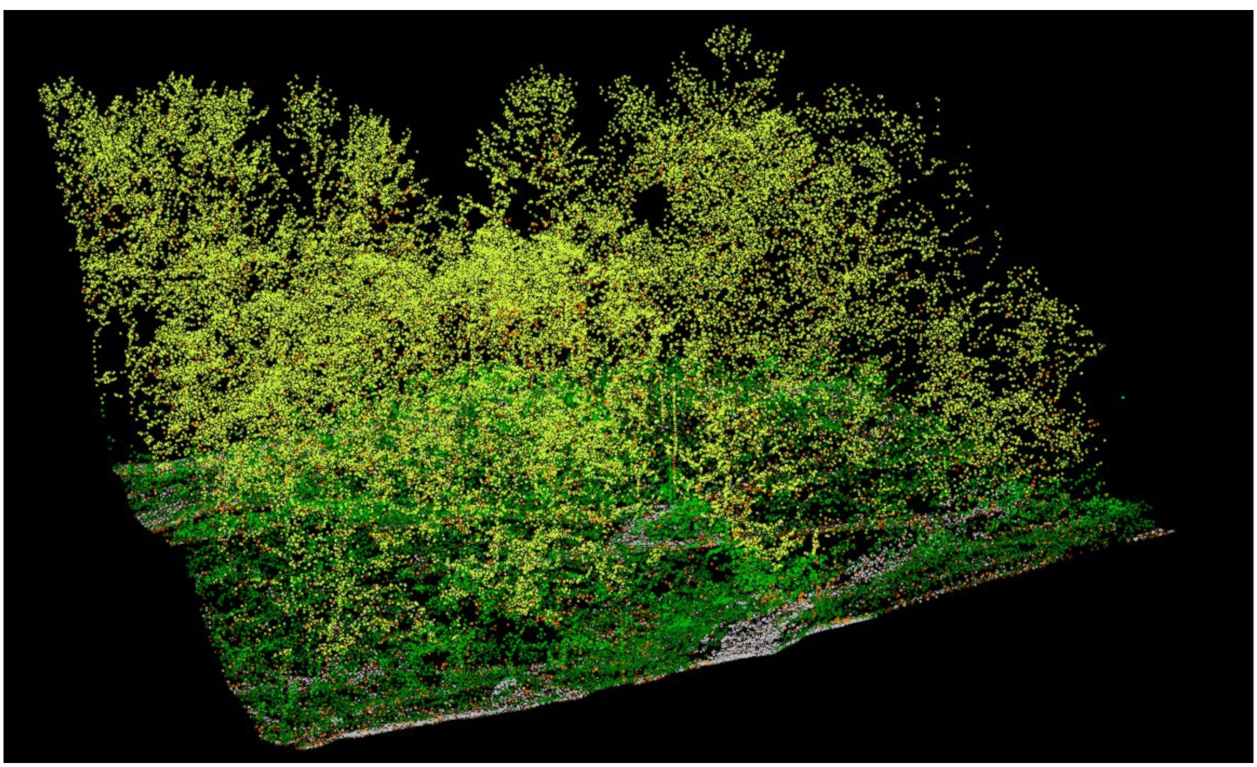
Pole sapling (deciduous) cross section 2 (same plot as above)



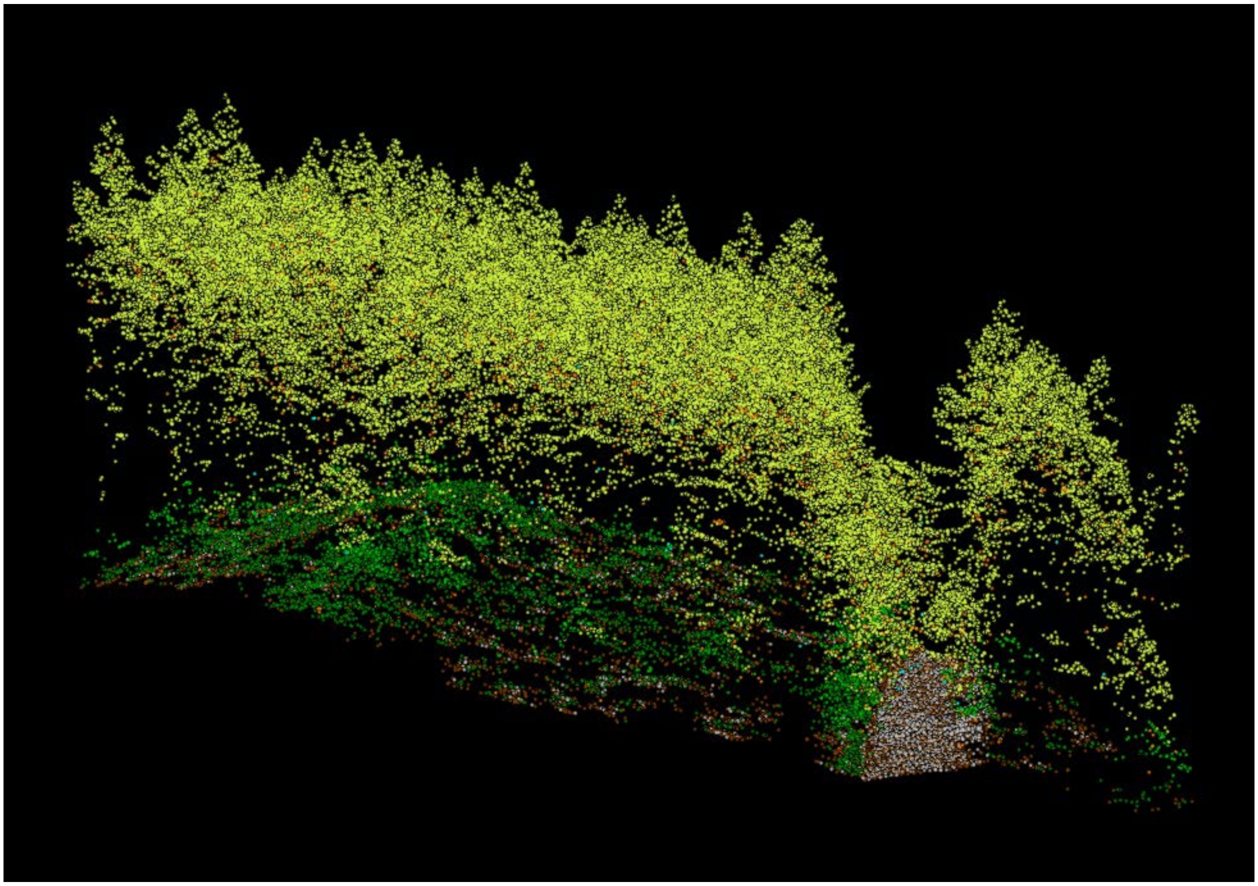
Young forest short (deciduous) cross section 1



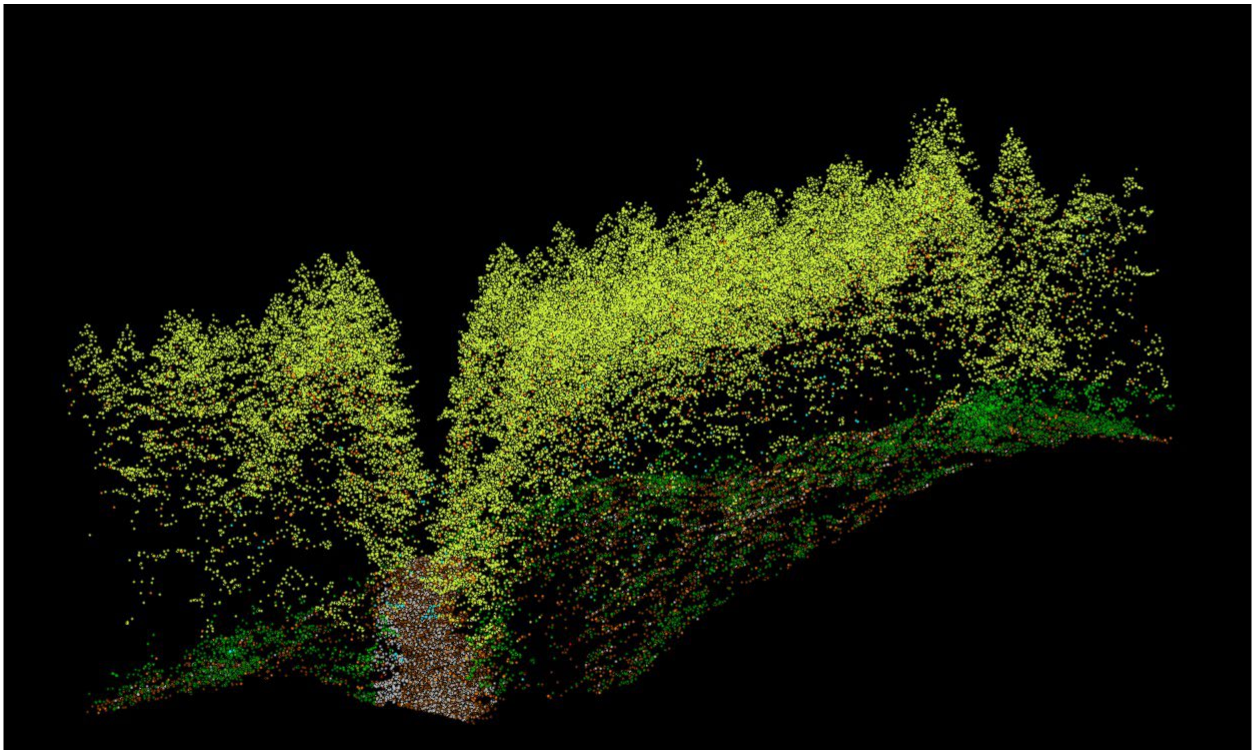
Young forest short (deciduous) cross section 2 (same plot as above)



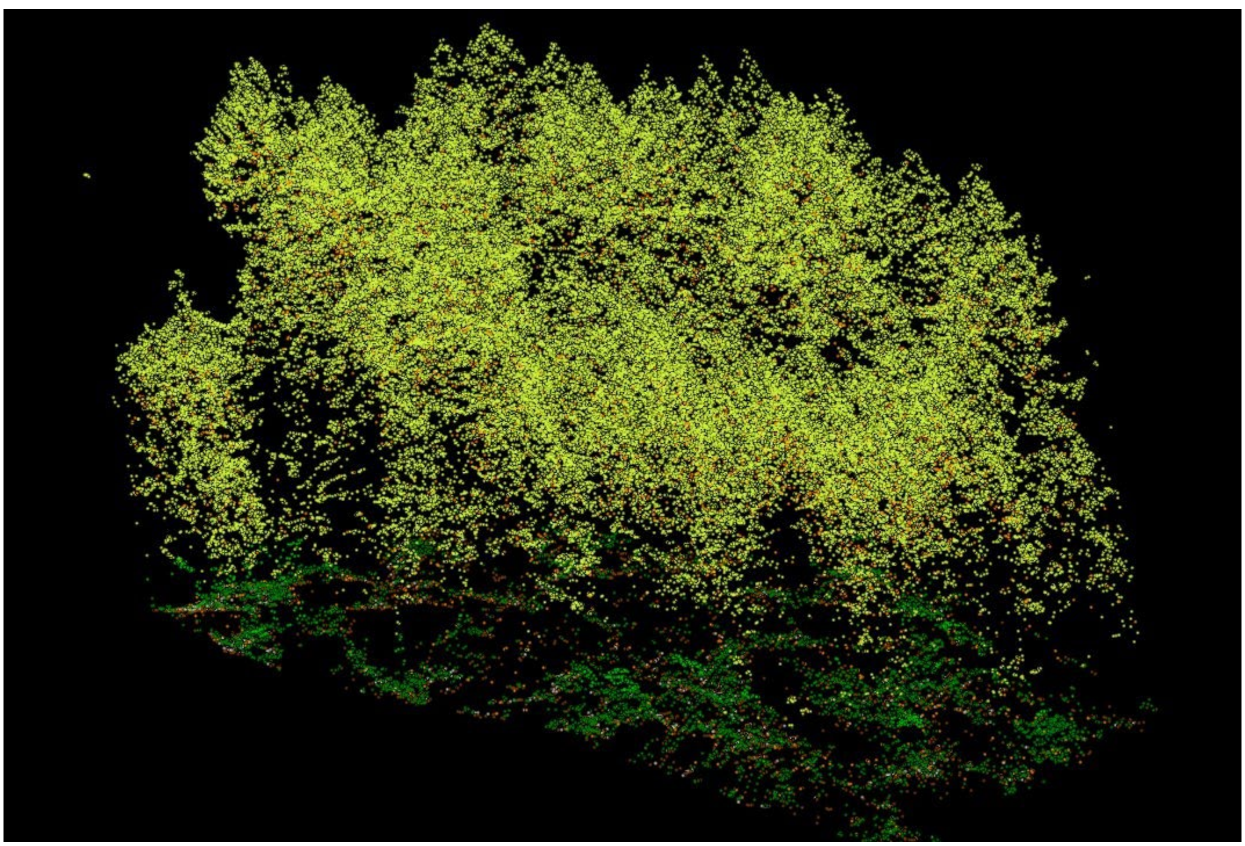
Young forest tall (deciduous) cross section



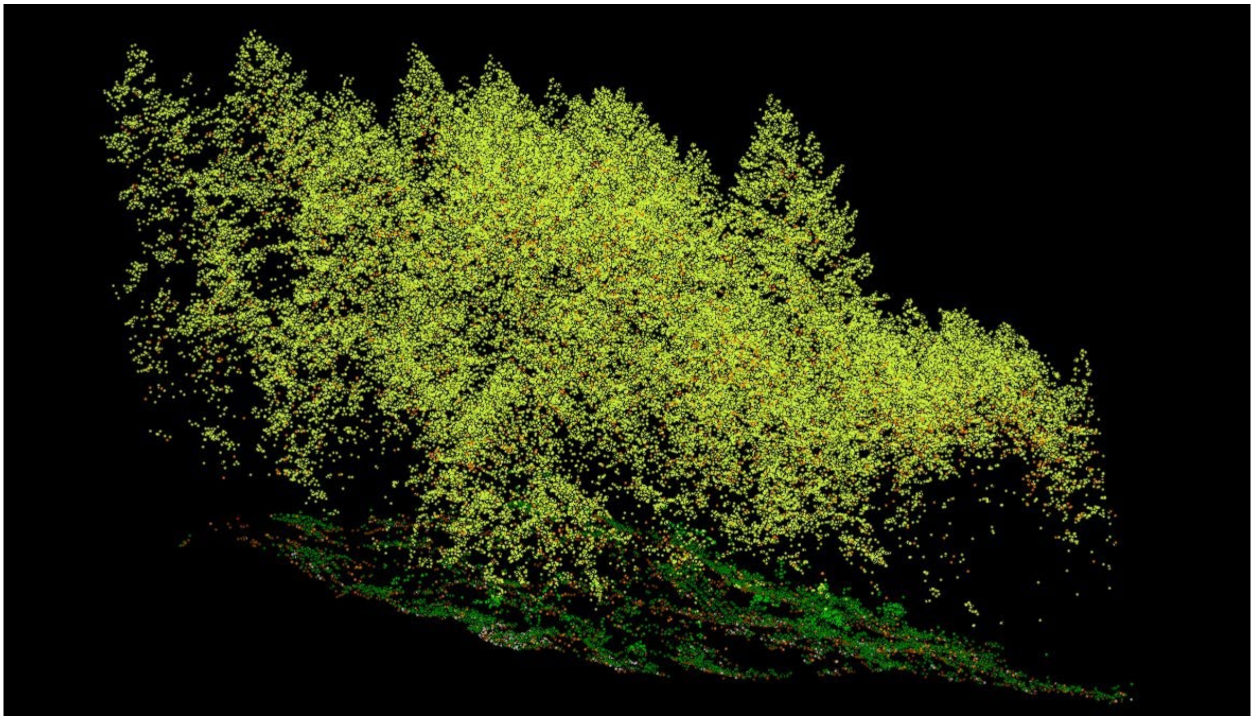
Mature forest (conifer) cross section 1



Mature forest (conifer) cross section 2 (same plot as above)



Old forest (conifer) cross section



Old forest (conifer) cross section (same plot as above)

Core wood samples were taken at 16 representative ground sampling plots across the City to help verify tree ages within each successional stage. It was found that in some forests there can be older trees mixed in with a younger generation of trees. This was the case where forests have been partially cleared or thinned in the past. In these cases, the stand was designated a successional stage that best reflects the more prominent canopy.

Thirteen samples were taken from young forest stands. The ages ranged from 23 to 80. In many of these stands there were older trees remaining with ages from 95 to 180. One sample was taken in a mature stand. The sample was not complete and the age was estimated as 145-155 years. Two samples were taken in stands classified as Old forest with ages estimated at 150-170 and 130-150.