Boulder at the (Tree) Top:
Considerations for the Future of Our Urban Canopy

By
Natalie Sterling Buchholz
University of Colorado at Boulder

A thesis submitted to the
University of Colorado at Boulder
in partial fulfillment of the requirements to receive
honors designation in
Environmental Studies
May 2019

Thesis Advisors:
J. Terrence McCabe, Anthropology, Committee Chair
Dale Miller, Environmental Studies Program
Peter Newton, Environmental Studies Program

Supplemental Advisors:
Margo Josephs, City Liaison and Interim Tree Trust Chairwoman, PLAY Boulder
Brett KenCairn, Senior Environmental Planner, City of Boulder
Thomas Read, Forester, City of Boulder Forestry Department

ABSTRACT:

The following study investigates how canopy and land cover differ across land use types in six study areas in the City of Boulder, Colorado. Canopy cover fluctuates as pests and diseases impact trees and can affect the area by proving or failing to buffer extreme weather (such as floods) and minimizing or exacerbating the heat island index. It is hypothesized that: 1) urban land use areas (such as outdoor malls) will have significantly lower canopy cover and dramatically higher impermeable surface areas than other land use types; 2) nearby neighborhoods will have statistically similar tree cover and ash tree densities; 3) study areas that currently have high canopy cover would receive disproportionately high benefits from small increases in canopy cover compared to study areas with low canopy cover; 4) all six study areas would benefit from large increases to canopy coverage. In this assessment six GIS surveys, two neighborhood case studies, and future scenario projections were employed to understand current canopy conditions, impacts of the Emerald Ash Borer (an invasive pest), and the achievability of expanding Boulder's urban canopy. It is found that highly urbanized areas (such as outdoor malls) have significantly less canopy cover and significantly higher impermeable surface cover than nearby suburban neighborhoods (which feature high canopy cover, above 28%, and lower impermeable surface cover, below 42%). Additionally, it is noted that case study neighborhoods, which are 3.5 miles apart, are statistically similar to one another in terms of tree density, prevalence of ash trees (which are investigated due to an Emerald Ash Borer infestation), and presence of infested ash trees. Future growth scenario projections (assessing 2%, 4%, and 10% increases in canopy coverage per study area) found that minimal canopy increases (2%) in suburban neighborhoods, and high canopy increases (6%) in highly urbanized areas offered similar returns on investment, though achievability in both scenarios was limited. I make

recommendations to decrease impermeable surface cover in all study areas through green roof initiatives (highly urban environments), as well as planting new trees in and maintaining current canopies (suburban neighborhoods).

PREFACE:

When I first set out to design, test, and carry out my thesis I met with Brett KenCairn, The City of Boulder's Senior Environmental Planner, to discuss what would be helpful and relevant to the city. Originally, I wanted to evaluate the potential for building a carbon sequestration portfolio of standards for The City of Boulder as part of our commitment to the Carbon Neutral Cities Alliance (CNCA). I had been inspired to innovate ways of monitoring carbon by The CNCA summit that Boulder hosted in September of 2018. There I heard speeches from global delegates representing their cities, all with their own commitments for carbon neutrality. This is where I got the idea to focus on carbon sequestration, though not at the scale that I eventually refined my project to.

After a long conversation with Dale Miller (the environmental studies honors chair) about the reality of honors theses, especially in terms of time constraints, I decided to narrow my project down to one aspect of carbon sequestration: trees. I then took this more refined topic back to Brett KenCairn and asked what research had already been conducted on Boulder's trees. It was then that I was first shown GIS mapping results for the entirety of The City of Boulder. This GIS data informed the city that its average canopy cover was at 15.9% at the time of collection in 2018. This overarching data made me question if there were variations across different land use types in the city, and when I learned that this had not yet been evaluated I found the new focal point of my thesis.

It was at this point that Brett introduced me to Margo Josephs, the interim chairwoman of PLAY Boulder's Tree Trust. The Tree Trust, a new branch of the Parks and Recreation non-profit PLAY Boulder, had just recently been established in order to better oversee urban canopy initiatives as they grew in popularity. Margo immediately took interest in the project and saw potential for a partnership between the Tree Trust and my ongoing thesis. Together, we determined which neighborhoods in the city should be evaluated via GIS and what criteria should be collected from the ground. Margo also encouraged me to read the City of Boulder Urban Forest Strategic Plan which she, and colleagues from the Parks and Recreation department, as well as city foresters, co-authored. This document introduced me to the problem of Emerald Ash Borers as pertaining to The City of Boulder.

Once my preliminary GIS data had been collected, I set out to conduct door to door surveys in the Martin Acres and Aurora 7 neighborhoods in order to assess the impact of Emerald Ash Borers. This portion of the project would not have been possible without Margo Josephs assistance in procuring survey maps and her connection to the city's forestry department. At this point, Margo introduced me to Thomas Read, one of the city's foresters. Thomas graciously gave me all of the materials I would need to understand the scope of Boulder's emerald ash borer infestation and gave his time to train survey volunteers. His training covered the history of the emerald ash borer in Boulder, how to identify ash trees, and how to identify signs of infestation. With this information at our disposal, the volunteers and myself were then able to conduct my surveys.

Throughout this process I was coached by two university-affiliated advisors (in addition to Dale Miller): Terrance McCabe from the University's anthropology and environmental studies departments, and Peter Newton from the Environmental Studies Program. Their experience and expertise, along with their poignant questions, helped form this thesis into what it is now. Without their background in research-style writing, my project would not have been the complete piece that it is.

I would like to express my thanks to the follow people: My CU advisors, Dale Miller, Terrance McCabe, and Peter Newton for their input, advice, and support throughout this process. My non-university associated advisors, Brett KenCairn, Margo Josephs, and Thomas Read for shaping this project and its relevance to the City of Boulder, Colorado. My friends, Anne Bennett and Chloe Mathis for humoring my constant tree babble. My wonderful partner, Jack Huun, who completed all of the door to door surveys by my side, was there for every nervous breakdown, and reminded me to celebrate every small victory. My sibling, whose puns and jokes about my “Treesis” kept me sane. My mother, whose questions about my project and my progress kept me on track. And my father, whose quiet pride is the greatest honor, achievement and accolade I could receive.

Words will never be enough. I thank you.

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CHAPTER 1: OVERVIEW

This thesis focuses on tree canopy cover in The City of Boulder, Colorado. My research question asks, “how does canopy cover and land cover vary across different types of land use in the City of Boulder?” In order to answer this question, I will compare the City of Boulder’s average canopy cover (15.9%) to six study areas across the city with different land use types, perform case studies in order to examine the potential impact of Emerald Ash Borers on two Boulder neighborhoods, and explore the achievability and benefits of growing the canopy an additional 2%, 4%, and 10%.

My hypotheses are as follows: 1) Urban land use areas (such as outdoor malls) will have significantly lower canopy cover and dramatically higher impermeable surface areas than other land use types. 2) Nearby neighborhoods will have statistically similar tree cover and ash tree densities. 3) Study areas that currently have high canopy cover will receive disproportionately high benefits from small increases in canopy cover compared to study areas with low canopy cover. 4) The six study areas will benefit from large increases to canopy coverage.

This thesis used the following methods: an analysis of current data sets and literature on urban tree canopies, GIS system modeling to calculate the current land use cover in the six study areas, an on the ground survey to assess the ratio of ash trees (which are vulnerable to the Emerald Ash Borer) to non-ash trees in two neighborhood study areas, and calculations to extrapolate on current sequestration masses and economic value of carbon removal from the atmosphere (increase 2%, 4%, and 10%).

This thesis will begin with a background section, which will give a brief history of canopy cover in The City of Boulder, Colorado. I will then delve into a review of relevant literature, focusing on known benefits of an urban canopy. Once the background research is established, I will describe the methods I deemed appropriate for this project and why I chose them. These methods will culminate in my findings: an assessment of the current canopy, ash tree density case studies conducted in two Boulder neighborhoods, a comparative analysis of a 2%, 4%, and 10% increase in canopy coverage across study areas, and a summation of these findings. These findings will inform recommendations for increasing or maintaining canopy cover, as well as increasing other non-impermeable surface cover types.

CHAPTER 2: BACKGROUND INFORMATION

A Brief History of Boulder's Urban Canopy

The City of Boulder is situated in Boulder County, Colorado, nestled against the front-range foothills. The City of Boulder was founded in 1871, though its story began long before with occupation by the native Southern Arapahoe tribe. When the city was founded, it was a fairly treeless place. The predominant natural land cover was arid grassland, except for further into the mountains where pine and deciduous trees still form mountain forests. It wasn't until the railroad reached the City of Boulder in 1873 that citizens were able to ship in non-native trees to the area. These trees, one of the most popular of which was ash, were planted by homeowners on private land and city officials on public land (History of Boulder, 2018).

The Improvement of Boulder, Colorado, published in March of 1910, is one of the earliest to discuss the placement and selection of street trees in The City of Boulder. After noting that, "Everyone must admit that the planting of silver maples and cottonwoods has been overdone," this document recommended the following twelve large, non-fruit tree species: 1) Thorn-less Honey Locust, 2) Red Oak, 3) White Oak, 4) Horse-chestnut, 5) Sugar Maple, 6) Western Catalpa, 7) American Ash, 8) European Linden, 9) Pin Oak, 10) Scotch Elm, 11) Norway Maple, and 12) Kentucky Coffee Tree. This early determination of twelve dominant tree species resulted in a canopy that was defenseless against the quick spread of pests such as the Emerald Ash Borer (discussed at length in chapter 5), and Dutch Elm disease, which swept through Colorado in the 1940's, and again in the late 1960's to early 1970's (Beaty, 2018). Additionally, *The Improvement of Boulder, Colorado* (1910), recommended that one tree species and one pruning method should be employed across the entirety of straight-line (nonmeandering) streets. This further weakens the canopy's defense against pests and diseases because closely planted trees of the same species are likely to simultaneously become infested or ill, leading to a canopy collapse. It has since been noted that a more biodiverse canopy is necessary to prevent canopy collapses. The City of Boulder now recommends 18 large, non-fruiting tree species with a higher emphasis on species of oak in addition to edible-fruit trees, shrubs, and small trees in the lower canopy (City of Boulder Forestry, 2019). The city no longer recommends planting ash trees due to an emerald ash borer infestation, which is discussed at length in chapter 5.

Since the City of Boulder was established on a high altitude, arid grassland, maintaining a canopy would prove to be difficult. Water scarcity had already shaped the land with native trees preferring to line river banks or remain high in the mountains where winter snow and ice provides moisture. However, the City of Boulder's original tree recommendations (as listed above) were comprised of predominantly non-native hardwood species chosen for their New England feel and familiarity. This primed the canopy for failure, as issues such as water intensity and pest and disease control were not considered. It is necessary to stress the importance of choosing the right trees and planting layout because these decisions dramatically impact the longevity of an urban canopy. Now, due to an early emphasis on planting ash trees and the advent of the emerald ash borer, the city is faced with the potential loss of up to 25% of its canopy (~12% on public property, and ~12% on private property).

BENEFITS OF URBAN CANOPIES:

The national average for urban tree cover is 27.1%, with forested regions having higher percentages of cover (about 34.4%) and desert areas having lower percentages (about 9.3%) (Dwyer et al., 2000). The City of Boulder's urban canopy cover is closer to the national average for grassland regions (17.8%) at 15.9%, which is in line with its natural arid grassland cover (City of Boulder Urban Forest Strategic Plan, 2018). Canopy cover, regional climate conditions, and impermeable surface area cover all contribute to the overall costs and benefits of maintaining an urban canopy. The greater the land use change was for an urban area, the greater the benefits an urban forest can provide. According to David Nowak (1995), the net benefit of an urban canopy comes down to a combination of four interacting components: 1) the impact from and on temperature and microclimates (see 2.2.1: Heat Island Index), 2) the absorption of pollutants (see 2.2.2: The Value of Clean Air), 3) organic volatile compounds emitted from trees (example, pollen) and emissions related to tree maintenance (example, exhaust from chain saws) (see 2.2.3: Volatile Organic Compounds), and 4) energy and emission savings due to increased efficiency of shaded buildings (see 2.2.4: Efficiency and Emissions).

Additionally, urban forests can help protect towns and cities from natural disasters such as flash floods. Storm water runoff wreaks havoc on urban areas because a high percentage of impermeable surfaces keeps rainwater from being absorbed where it falls, causing local reservoirs (such as streams, rivers, and ponds) to overflow. One study from Dayton, Ohio found that its canopy cover (22%) reduced storm water runoff by 7%, and an additional 7% increase in canopy coverage could boost these reductions to 12% (Sanders, 1986). The City of Boulder states that its urban canopy is estimated to save the city $177,000 per year in avoided storm water runoff damages (City of Boulder Urban Forest Strategic Plan, 2018).

HEAT ISLAND INDEX

As stated in *The City of Boulder Urban Forest Strategic Plan*, "An urban heat island (UHI) is an urban area or metropolitan area that is significantly warmer than its surrounding rural areas due to human activities (2018).” UHIs are strongly correlated to land use change and impermeable surface area. When ground cover is shifted from natural vegetation to urban or suburban environments, the ecosystem services that the environment provides are also impacted. For example, in a study conducted by Imhoff and colleagues, 85% of UHI temperature anomalies in previously forested areas can be attributed to urbanization and land use change. The same study also found that in all study cities (with the exception of cities built within desert ecosystems) about 70% of land surface temperature was attributable to impermeable surface areas, and urban areas were on average 4.3ºC and 1.3ºC warmer in the summer and winter, respectively, than non-urban areas (2010). This study illustrates the connection between urbanization, impermeable surface areas, and UHI; the greater the land cover changes, the greater the UHI anomalies will be.

In order to mitigate the impacts of UHI, it is essential to strategically plan the layout of an urban forest. When solar radiation reaches impermeable surfaces (such as cement, buildings, and roads), it diffuses back off of the surface, heating the surrounding area and adding to the impact of UHI. Shading impermeable surfaces with canopy reduces the amount of solar radiation that reaches these surfaces, thus preventing radiative heat from leeching back into the environment. Strategically planting trees along stretches of roads, adjacent to sidewalks, and surrounding buildings drastically reduces the UHI temperature anomaly. For instance, one study found that evapotranspiration in combination with shading from trees can diminish summer temperatures by 2ºf to 9ºf (1ºC to 5ºC) in addition to sequestration and air filtering benefits (Huang et al., 1990).

The Value of Clean Air

Trees play a major part in the sequestration of carbon and other compounds. The urban forest’s role is important because of its unique location: close to the source of pollutants. It is estimated that in the United States alone, urban forest trees store an equivalent of five and a half months of the US's carbon emissions, and the annual sequestration of US urban forest trees is estimated to be equal to five days of the US population's carbon emissions (Nowak and Dwyer, 2007). The composition and placement of an urban forest should be considered carefully depending on an urban area's needs. Strategically planting trees along busy roads, for example, can recapture a number of compounds emitted from vehicles passing by. In fact, one London-based study found that street trees take up more particulate matter than any other planting type, removing upwards of 27.3kg of PM10 per hectare of coverage each year (Tallis et al., 2011).

While placement of trees is important, it is equally crucial to consider what kinds of trees are best for the job. Hardwood trees sequester 46% to 50% of their weight in carbon whereas conifers and soft woods sequester between 47% to 55% of their weight in carbon. This is because lignin has the highest carbon content of all tree molecules and softwoods contain around 10% more lignin than hardwoods. As a tree ages, the newly formed wood begins to have a higher cellulose to lignin ratio than that of a young tree, thus sequestering less carbon as it ages. However, hardwood species are denser than softwoods, giving them a greater amount of carbon content per unit volume. In essence, a low carbon content hardwood, if growing fast enough, can out-sequester a similarly aged softwood in a growing season (Lamlom and Savidge, 2003).

Once a tree has been chosen and properly placed, it is crucial to maintain the health and well-being of that tree for the entirety of its lifetime. McPherson and colleagues (1997) tell us that large healthy trees can remove up to 60 to 70 times more pollution than smaller trees of the same species. This is mostly because larger, better established trees tend to have a higher leaf area index (the estimated combined area of all the leaves on a single tree). As trees grow, their leaf area index increases, creating more surface area for gas exchange between the tree and its environment. So, while young, fast growing trees may store more carbon per year than older trees, the larger trees will remove more pollutants from the air on an annual basis than their younger counterparts.

In economic terms, trees contribute to savings from avoided air quality related health concerns, such as asthma, and reduce the cost of mechanically removing pollutants from the atmosphere. In the City of Boulder alone urban trees were valued at $676,508 in carbon dioxide reductions per year and their annual air quality improvement was valued at $22,631. The city's trees were also estimated to have a long-term carbon storage value of $17,056,868. These trees are considered so valuable because of their filtration capabilities, protection from weather extremes, and aesthetic value. The estimated cost to replace the city's urban canopy has been appraised at $109,955,170 (City of Boulder Urban Forest Strategic Plan, 2018).

Estimations of economic value of tree canopies come from services they provide and the estimated value of these services (Calculate the Value of a Tree, 2017). For example, trees remove pollutants such as particulate matter from the air (service provided). This service reduces the number of asthma related hospitalizations in well forested areas. The value of this service can be calculated using the cost of emergency asthma treatments by comparing the number of asthma patients in similarly affluent areas with dissimilar tree covers. In an imaginary scenario let's say that City A is well forested and receives an average of five asthma patients to its emergency room per year. City B, while similar in every other way, is poorly forested and receives twice as many asthma patients to its emergency room per year (ten patients). If the cost of emergency asthma treatment is $5,000, then City A's value of avoiding those additional five patients is $25,000. Since the two cities only differ in canopy cover, the $25,000 in medical savings is attributed to its urban canopy and adds to its overall value.

VOLATILE ORGANIC COMPOUNDS

Volatile organic compounds (VOCs) are air pollutants that are emitted by trees (such as terpenes and pollen) and are known to be a factor in the creation of ground level ozone and carbon monoxide (Brasseur and Chatfield, 1991). However, the release of VOCs is affected by temperature, with higher temperatures yielding higher release densities. Since high tree cover is associated with lower air temperatures, it is thought that a high enough canopy density would mitigate VOC damages by reducing their emissions. For example, a computer simulation of ground level ozone in Atlanta, Georgia showed that a 20% loss in urban canopy cover, and related rise in air temperature, could increase ground level ozone intensity by 14% (Cardelino and Chemeides, 1990). Another computer model study focusing on New York City found that a 10% increase in tree cover could lead to ozone reductions of 4ppb, which is equal to 37% of the ozone reduction NYC needs to meet the National Ambient Air Quality Standards (Luley and Bond, 2002).

While canopy coverage plays a large role in the emission and effects of VOCs from trees, the specific trees chosen for urban environments also have an impact. Trees from the *Fraxinus* (ashes), *Ilex* (holm oaks), *Malus* (apples), *Prunus* (stone fruits), *Pyrus* (pears), and *Ulmus* (elms) genera typically have low VOC emissions while trees from the *Eucalyptus, Quercus* (oaks), *Platanus* (plane trees), *Populus* (cottonwoods), *Rhamnus* (buckthorns), and *Salix* (willows) genera are typically high VOC emitters (Benjamin et al., 1996). In a scenario where there is low canopy coverage, it would be ideal to choose species that come from a low emitting genus while a higher canopy covered area would warrant less concern over species-based emissions.

EFFICIENCY AND EMISSIONS

Strategically planted trees generate savings by increasing the efficiency of a building's cooling and heating systems. Well placed trees around a building act like an extra layer of insulation, keeping solar radiation from reaching the building during the summer and preventing cold winds from reaching the building's surface, resulting in heat loss during the winter. The impact of trees is not small, in fact Heisler and DeWalle (1968) found that trees can lower solar radiation and wind speed by up to 90% compared to treeless areas. This reduced solar radiation can translate into temperature reductions of 20ºF to 45ºF on building surfaces, and up to 45ºf reductions in parked cars. In the City of Boulder, it has been estimated that as few as three strategically placed trees can save between $100 and $250 in annual energy costs (City of Boulder Urban Forest Strategic Plan, 2018). Another study found that heating costs can be reduced by up to 25% simply by planting trees around a heated structure (Heisler, 1986).

CHAPTER 3: METHODOLOGY

I-TREE CANOPY METHODOLOGY

For my thesis I used the i-Tree Canopy modeling tool (version 6.1) from i-Tree tools. This modeling system allows the user to select a study area and imports the most recent images from Google Maps to generate an up to date canopy report. The tool works by selecting points at random within the designated study area for the user to identify as tree or non-tree coverage. While the program only uses a tree versus non-tree ratio to calculate current coverage and economic value of the canopy, I am including other non-tree cover information in my report. The non-tree coverage options that I have worked with are shrub, grass, non-tree, and impermeable surfaces.

The coverage options (tree, non-tree, impermeable surface, grass, and shrub) are defined as follows: The *Tree* option designates an area covered by a tree's canopy. The *Non-tree* option refers to any permeable surface that is not grass (such as dirt, sand, gravel, water surfaces that are not a swimming pool, and turf sports fields). The *Impermeable Surface* option denotes a piece of land or building that water cannot sink through (such as pavement, a building, or solar panels). The *Grass* option is used for data points that are located on grassy surfaces, and *Shrub* is used to designate larger plants that are not considered trees, such as bushes. These coverage options were chosen in order to assess canopy cover as well as the study area's treeless foliage cover and impermeable surface cover.

It is important to quantify the impermeable surface cover in addition to canopy coverage because impermeable surfaces have a high impact on environmental factors such as the heat island effect and water runoff. High amounts of impermeable surfaces lead to high temperatures associated with the heat island effect and creates high run-off zones during storms. This runoff can be catastrophic in the case of flooding since storm water will not be absorbed where it fell. Thus, neighborhoods and areas in Boulder with high rates of impermeable surfaces will likely feel greater impacts from storms and floods.

The i-Tree Canopy tool uses coverage estimates to determine annual savings and particulate removal from the area's tree population. The values measured by this model are: Carbon Monoxide removed annually (CO), Nitrogen Dioxide removed annually (NO2), Ozone removed annually (O3), Particulate Matter less than 2.5 microns removed annually (PM2.5), Sulfur Dioxide removed annually (SO2), Particulate Matter greater than 2.5 microns and less than 10 microns removed annually (PM10), Carbon Dioxide sequestered annually in trees (CO2seq), and Carbon Dioxide stored in trees (CO2Stor, not an annual rate). These values are reported in US dollars and pounds and are given standard error margins.

To generate a study report, I first needed to select my study areas. The areas chosen for study are as follows: Pearl Street Mall and surrounding urban area, 29th Street Mall, The University of Colorado, Boulder main campus, the Aurora 7 neighborhood, the Harlow Platts neighborhood, and the Martin Acres/Table Mesa neighborhood. These six areas were chosen specifically to examine the differences between highly urban areas (Pearl Street Mall and 29th Street Mall) and neighborhoods (Aurora 7, Harlow Platts, Martin Acres/Table Mesa). The University of Colorado Boulder main campus was chosen to act as an intermediate between the two land use types, as it falls more between than within either category. I selected the two outdoor malls because of local familiarity and popularity. The three neighborhood areas were proposed to me by Margo Josephs, who believed that examining these areas would help the city assess the efficacy of its tree-related educational programs.

Once my study areas had been chosen, I was able to begin my GIS surveys. The i-Tree Canopy tool allows you to designate the study areas by drawing a red boundary around a chosen neighborhood or urban region. Once the study area has been outlined, the user is prompted to designate what country, state, and county the area is located in, as well as choose whether the area is urban, rural, or both. For this study, all selected areas are located in The United States, Colorado, Boulder, and were designated as urban areas. It is important to input this information because the climate conditions, as well as environmental conditions seen in urban versus rural areas shape what calculations are used in the final canopy report.

In order to ensure higher quality and accuracy of i-Tree Canopy reports, it is recommended to have a high number of data points per study. My research used a minimum of 500 points per study location as well as a maximum standard error value of ±1.50%. This standard margin of error will help ensure consistency across different sized study areas. For example, the 29th Street Mall study area was the smallest surveyed, only requiring 599 data points to reach the ±1.50% maximum SE margin, while the largest study area, The University of Colorado, Boulder main campus, required 1,097 Data points.

CONVERSIONS AND CALCULATIONS

IMPERIAL UNITS TO METRIC UNITS

For the purpose of putting my data into internationally accepted units, I have decided to convert the units of mass reported by i-Tree Canopy (which are in imperial units) to metric units. The following are the conversion rates I used:

Pounds (lb) to Kilograms (kg)

1lb = 0.453592kg

US Tons (UST) to Metric Tons (MT)

1UST = 0.907185MT

Conversions were conducted on Microsoft Excel and were then rounded to the nearest two decimal places (ex: 1.05).

Sequestration values were also reported in USD, which are listed in my report for reference by the City of Boulder and Boulder Tree Trust. However, it is important to note that these values represent a snapshot in time. The monetary value of sequestration can and will change overtime due to variables such as: 1) the value of a statistical life, and 2) the cost of atmospheric-pollutant related healthcare treatments (such as asthma treatments).

Tree Cover to Impermeable Surface Cover Ratio Calculations

Calculations for tree cover to impermeable surface cover ratios relied on the following formula:

$$\frac{\text{tree cover of x study area}}{\text{impermeable surface cover of x study area}}$$

Calculations for tree cover to impermeable surface cover ratios were conducted in Microsoft Excel and reported as proportions (ex: 0.15) with proportions closer to 1 having a more even distribution between the two coverage types.

Neighborhood Survey Methodology

In addition to the i-Tree Canopy assessments, two neighborhood study areas (Aurora 7 and Martin Acres) were surveyed for the ratio of ash trees to non-ash trees in order to evaluate canopy health and potential risk of loss due to the Emerald Ash Borer. In order to assess an area's specific canopy loss, I assembled volunteers from the Boulder Tree Trust to assist in the two surveys. Survey volunteers were trained to identify white and green ash trees and signs of Emerald Ash Borer infestations through a one-hour training hosted by myself and Thomas Read of The City of Boulder's Forestry department on January 30th, 2019. Volunteers who could not make this training were prepared for the survey by myself at a later date. The training taught volunteers the basic diagnostic traits for green and white ash trees: 1) Alternating bud patterns, 2) compound leaves with leaves five to eleven oppositely arranged leaflets, and 3) light to dark gray bark that has characteristically diamond shaped grooves along a mature trunk or at the base of a younger tree's trunk (see appendix 1). In order to ensure accuracy of identification in the field, volunteers were also asked to download the City of Boulder's EAB/AshTreeID application onto their smart devices. This application poses a few simple questions that informs the user if the tree being examined is in fact an ash tree.

In addition to identification of ash trees, volunteers were taught how to identify the Emerald Ash Borer and signs that they have infested an ash tree. The signs of infestation the volunteers were taught to recognize were: 1) characteristic D shaped exit holes of about 1/8 of an inch wide, 2) damage to trunk and branches from woodpeckers (sections of bark peeled back with holes pecked into the inner bark), 3) epicormic sprouts (new growth off the trunk, below the crown), and 4) visible serpentine-shaped larval galleries where bark is missing (see appendix 2). After being trained, volunteers signed up to survey either one or both of the selected neighborhoods. These surveys occurred February 9th and 10th, 2019 with the aid of The Boulder Tree Trust, a subsection of the non-profit, PLAY Boulder.

Property addresses were retrieved from The City of Boulder's interactive mapping system and relayed to me for the purpose of these two neighborhood surveys. Due to time restrictions, I decided that I would randomly sample 25% of the addresses from each neighborhood in the study. Using a random-number generator and Microsoft Excel, addresses were sampled and assembled into a street, address number, and parcel number (for city reference) format. The sampled addresses were then assembled into walkable routes (three routes per study) and were assigned to volunteers on the day of each survey. Each property was to be assessed for: 1) whether the property resident answered the door (yes or no), 2) whether the property resident granted surveyors access to their yards (yes or no), 3) how many trees total were on the property, 4) how many of these trees were ash, and finally, 5) whether any ash trees on the property show signs of Emerald Ash Borer infestation (yes or no).

Each survey began at 1pm at a designated meeting point (for Aurora 7 it was High Peaks Elementary School at 3995 Aurora Avenue, and for Martin Acres is was Creekside Elementary School at 3740 Martin Drive). Once all the volunteers had assembled, I conducted a review of training information and practiced identifying ash trees and signs of infestation with the volunteers, pointing out diagnostic traits as I did so. After reviewing diagnostic information, the entire volunteer group visited three properties with answering residents so they could see how I wanted them to interact with residents and how to record data properly.

When the door was answered, volunteers were instructed to introduce themselves and the project with the prompt, "Hello! My name is (insert name) and I am conducting an ash tree survey in your neighborhood on behalf of PLAY Boulder's Tree Trust. Do you know if you have any ash trees on your property?" If a resident said, "I'm not sure," volunteers would then respond along the lines of, "would you mind if I check your property for them? The city has an emerald ash borer infestation and we want to make sure residents are aware of any potential infestations." If a resident replied, "yes, I have ash trees," the volunteers would respond with, "would you mind if I check them for infestations?" If a resident replied, "no I do not have any ash trees," the volunteers would respond, "Great! Would you mind if I took a look at the other trees on your property?" All of the above prompts were designed to lead residents to agree to a tree count and infestation check on their property. Granted access often led to conversations about tree health and issues regarding the emerald ash borer. Whenever a volunteer felt unable to answer a question, they gave the asking resident Thomas Read's (from the city's forestry department) business card for more information. If at any time during the interaction a resident denied volunteers access, the volunteers would cease asking for entry, thank the resident for their time, and leave immediately.

Once I was assured the volunteers were comfortable interacting with residents, and their questions about identification and data collection were answered, I sent them off on their routes. I made a point to urge volunteers to call me anytime they had questions or concerns throughout the survey. Due to cold weather and limited daylight, the surveys concluded at 5pm; volunteers were encouraged to gather as much data as they could during this time. Since time to collect data was limited, only properties that were visited by surveyors were included in the analysis. To account for this, I have listed the proportion of visited properties out of the original randomly selected properties in my presentation of survey data.

Collected data was later synthesized into data tables with the following categories: 1) total properties in the study area, 2) number of properties visited, 3) visited properties where residents answered the door, 4) the number of visited properties whose residents gave surveyors permission to check their yards, 5) the total number of trees surveyed per neighborhood, 6) the total number of ash trees surveyed per neighborhood, 6) the percent of trees that were ash on surveyed properties, 7) the average (mean) number of trees per property surveyed, 8) the average (mean) number of ash trees per property surveyed, 9) the total number of properties surveyed that had signs of Emerald Ash Borer infestation, and 10) the percent of surveyed properties with signs of Emerald Ash Borer infestation.

METHODS FOR CASE STUDY T-TESTS

In order to conduct a proper statistical analysis, four T-tests were run comparing the Aurora 7 and Martin Acres datasets. All four T-tests were two-sample tests assuming unequal variance in order to account for different quantities of data points collected between the two datasets. I also chose to focus my analysis on the two-tailed T-test p-values in order to incorporate variance on both ends of the range.

The first T-test used the complete datasets from Aurora 7 and Martin Acres in order to determine mean, standard deviation, and p-value when comparing the average number of trees per property surveyed. The second T-test compared the average number of ash trees per property. The third T-test compared the average number of ash trees per property with ash trees present. The third T-test uses smaller datasets than the first two because I am only considering properties with ash trees, rather than all of the properties surveyed. The fourth and final T-test compared the number of properties with ash trees that had signs of infestation between the two datasets (again, only testing the properties that have ash trees). This T-test was run using a binomial system because the original data collected indicated either "yes" or "no" for signs of infestation. In order to run the T-test, indications of "yes" were assigned a value of 1 and indications of "no" became a value of 0.

CHAPTER 4: AN ASSESMENT OF BOULDER'S CURRENT CANOPY

The City of Boulder estimates that as of 2018 its average canopy cover is 15.9% (City of Boulder Urban Forest Strategic Plan, 2018). However, this does not consider regional differences across the city- primarily how urbanized the area is. I have hypothesized that areas of high building density (such as shopping centers and downtown districts) will have less canopy cover than areas with a lower building density (such as neighborhoods and university campuses), as reflected by google earth images. The following section will test this observational hypothesis and whether or not it is reflected in data collected with i-Tree Canopy modeling and 2018 google images.

In the following sections I will present data from the six study areas, describe trends in that data, and highlight my findings. The final section of this chapter will compare and contrast ground cover across the six study areas with a special focus on each area's tree to impermeable surface ratio.

29TH STREET MALL STUDY AREA

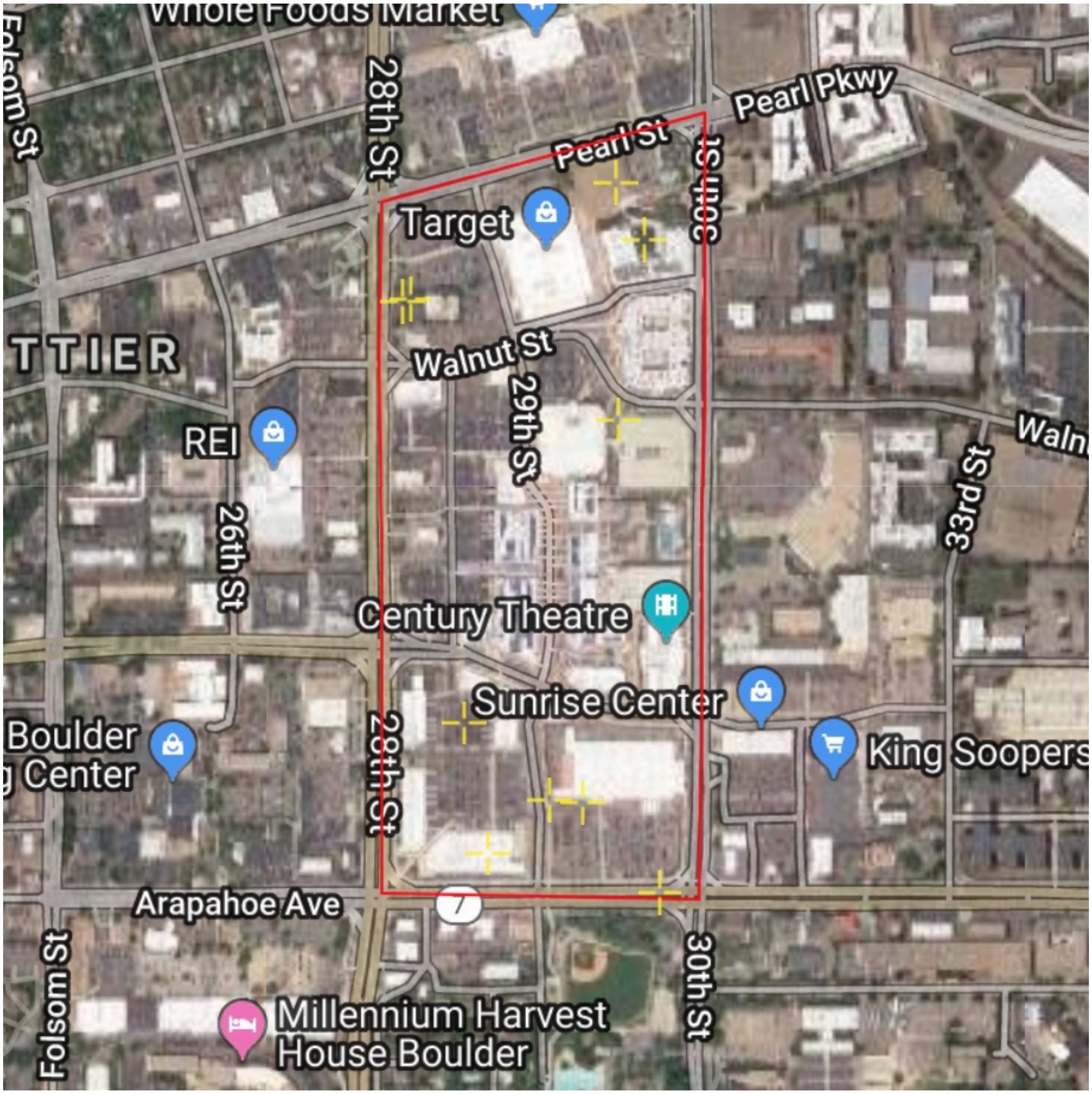

Image 4.1: The 29th Street Mall study area designated by a red line around its boundaries.

The 29th Street Mall study area, as seen in image 4.1, is dominated by an outdoor walking mall. The area is the first of two urban study areas selected for this study. The area, similar to the Pearl Street Mall study area, was selected because of the visibility of impermeable surface area cover. Aside from a few saplings, the area is mostly treeless. The study area is confined by

Pearl Street to the north, 30th Street to the east, Arapahoe Avenue to the south, and 28th Street to the west.

29TH STREET MALL'S I-TREE CANOPY RESULTS:

Cover Class	Description	Abbr.	Points	% Cover
Tree	Tree, non-shrub	T	36	6.01 ±0.97
Non-Tree	All other surfaces	NT	43	7.18 ±1.05
Impermeable Surface		IS	503	84.0 ±1.50
Grass		GR	7	1.17 ±0.44
Shrub		SH	10	1.67 ±0.52

Table 4.1.1: 29th Street Mall's estimated coverage, as reported by i-Tree Canopy, 2018.

The 29th Street Mall study area's ground coverage was calculated using the i-Tree Canopy tool. Relative percentages were determined for five ground cover types (Tree, Non-Tree, Impermeable Surface, Grass, and Shrub) through the generation of 599 random data points within the study area. The dominant coverage type was impermeable surface area (84.0 ± 1.50%), followed by non-tree (dirt or gravel) cover (7.18 ± 1.05%), tree cover (6.01 ± 0.97%), shrub cover (1.67 ± 0.52%), and grass cover (1.17 ± 0.44%).

Tree Benefit Estimates

Abbr.	Benefit Description	Value (USD)	±SE	Amount	±SE
CO	Carbon Monoxide removed annually	3.61 USD	±0.58	5.43 lb	±0.88
NO2	Nitrogen Dioxide removed annually	20.99 USD	±3.39	63.87 lb	±10.32
O3	Ozone removed annually	386.42 USD	±62.44	286.37 lb	±46.27
PM2.5	Particulate Matter less than 2.5 microns removed annually	132.49 USD	±21.41	9.35 lb	±1.51
SO2	Sulfur Dioxide removed annually	1.51 USD	±0.24	14.42 lb	±2.33
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	297.78 USD	±48.12	95.35 lb	±15.41
CO2seq	Carbon Dioxide sequestered annually in trees	617.56 USD	±99.79	17.52 T	±2.83
CO2stor	Carbon Dioxide stored in trees (Note: this benefit is not an annual rate)	24,106.90 USD	±3,895.21	683.78 T	±110.49

Table 4.1.2: Estimated Benefits from Canopy Cover in the 29th Street Mall study area, as reported by i-Tree Canopy, 2018.

The i-Tree Canopy tool used the data reported from the 599 randomly selected points for the 29th Street Mall study area to estimate the value (USD) of pollutant removal or sequestration performed by the trees in the study area. The highest value for annual rate of sequestration or removal was from carbon dioxide sequestered by the area's trees ($617.56 per year), followed by ground ozone removed ($386.42 per year), particulate matter greater than 2.5 but less than 10 microns ($297.78 per year), particulate matter less than 2.5 microns ($132.49 per year), nitrogen dioxide removed ($20.99 per year), carbon monoxide removed ($3.61 per year), and sulfur dioxide removed ($1.51 per year). The carbon dioxide stored in 29th Street Mall study area's trees is estimated to be valued at $24,106.90 (note this is not an annual rate, but the total estimated worth of storage).

Reported Mass Converted to Metric

Pollutant (metric weight)	Current Mass
CO (kg)	2.46
NO2 (kg)	28.97
O3 (kg)	129.90
PM2.5 (kg)	4.24
SO2 (kg)	6.54
PM10 (kg)	43.25
CO2seq (T)	15.89
CO2stor (T)	620.31

Table 4.1.3: The estimated mass of pollutants removed from 29th Street Mall on a yearly basis, converted to metric units. Note that in Figure # mass was reported in English units.

PEARL STREET MALL STUDY AREA

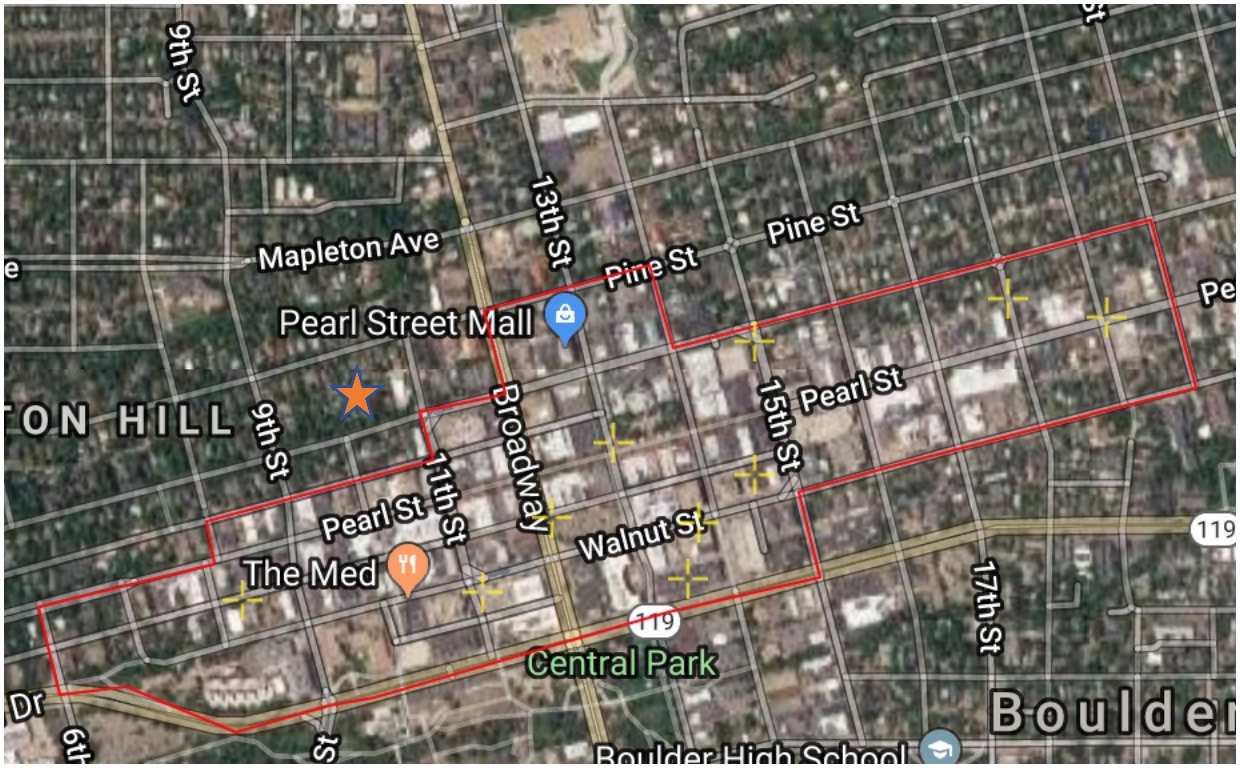

Image 4.2: The Pearl Street Mall study area is defined by the red line picture above.

Pearl Street Mall, as defined by the study area in red above, is dominated by a pedestrian mall limited to foot traffic along the length of Pearl Street. This area is the second of the two heavily urbanized areas being studied (the other being 29th Street Mall). It is widely recognized that high percentages of impermeable land surface correlate with urban areas; the Pearl Street Mall study area was chosen because it has a large amount of impermeable surface area that is visible via satellite imagery. The study area was defined by where a clear shift from impermeable surface cover to canopy cover occurs on satellite imagery from summer of 2018 and was limited by Pine Street to the north, 20th Street to the east, Boulder Canyon Drive/Canyon Boulevard to the south, and 6th Street to the west. A good example of this shift from impermeable surface to canopy cover occurs to the north-west of the corner of 11th Street and Spruce Street (designated by the orange star in Image 4.2).

PEARL STREET MALL'S I-TREE CANOPY RESULTS:

Cover Class	Description	Abbr.	Points	% Cover
Tree	Tree, non-shrub	T	84	13.6 ±1.38
Non-Tree	All other surfaces	NT	1	0.16 ±0.16
Impermeable Surface		IS	518	83.7 ±1.49
Grass		GR	16	2.58 ±0.64
Shrub		SH	0	0.00 ±0.00

Table 4.2.1: Pearl Street Mall's estimated coverage, as reported by i-Tree Canopy, 2018.

The Pearl Street Mall study area's ground coverage was calculated using the i-Tree Canopy tool. Relative percentages were determined for five ground cover types (Tree, Non-Tree, Impermeable Surface, Grass, and Shrub) through the generation of 619 random data points within the study area. The dominant coverage type was impermeable surface area (83.7 ± 1.49%), followed by tree cover (13.6 ± 1.38%), grass cover (2.58 ± 0.64%), and non-tree (dirt or gravel) cover (0.16 ± 0.16%). There was no shrub coverage reported for this data set.

Tree Benefit Estimates

Abbr.	Benefit Description	Value (USD)	±SE	Amount	±SE
CO	Carbon Monoxide removed annually	10.24 USD	±1.04	15.41 lb	±1.56
NO2	Nitrogen Dioxide removed annually	59.57 USD	±6.04	181.32 lb	±18.39
O3	Ozone removed annually	1,096.95 USD	±111.27	812.96 lb	±82.46
PM2.5	Particulate Matter less than 2.5 microns removed annually	376.12 USD	±38.15	26.54 lb	±2.69
SO2	Sulfur Dioxide removed annually	4.28 USD	±0.43	40.92 lb	±4.15
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	845.33 USD	±85.75	270.67 lb	±27.46
CO2seq	Carbon Dioxide sequestered annually in trees	1,753.13 USD	±177.83	49.73 T	±5.04
CO2stor	Carbon Dioxide stored in trees (Note: this benefit is not an annual rate)	68,434.52 USD	±6,941.72	1,941.11 T	±196.90

Table 4.2.2: Estimated Benefits from Canopy Cover in the Pearl Street Mall study area, as reported by i-Tree Canopy, 2018.

The i-Tree Canopy tool used the data reported from the 619 randomly selected points for the Pearl Street Mall study area to estimate the value (USD) of pollutant removal or sequestration performed by the trees in the study area. The highest value for annual rate of sequestration or removal was from carbon dioxide sequestered by the area's trees ($1,753.13 per year), followed by ground ozone removed ($1,096.95 per year), particulate matter greater than

2.5 but less than 10 microns ($845.33 per year), particulate matter less than 2.5 microns ($376.12 per year), nitrogen dioxide removed ($59.57 per year), carbon monoxide removed ($10.24 per year), and sulfur dioxide removed ($4.28 per year). The carbon dioxide stored in Pearl Street Mall study area's trees is estimated to be valued at $64,434.54 (note this is not an annual rate, but the total estimated worth of storage).

Reported Mass Converted to Metric

Pollutant (metric weight)	Current Values
CO (kg)	6.99
NO2 (kg)	82.25
O3 (kg)	368.75
PM2.5 (kg)	12.04
SO2 (kg)	18.56
PM10 (kg)	122.77
CO2seq (T)	45.11
CO2stor (T)	1760.95

Table 4.2.3: The estimated mass of pollutants removed from Pearl Street Mall on a yearly basis, converted to metric units. Note that in Figure # mass was reported in English units.

THE UNIVERSITY OF COLORADO, BOULDER MAIN CAMPUS STUDY AREA

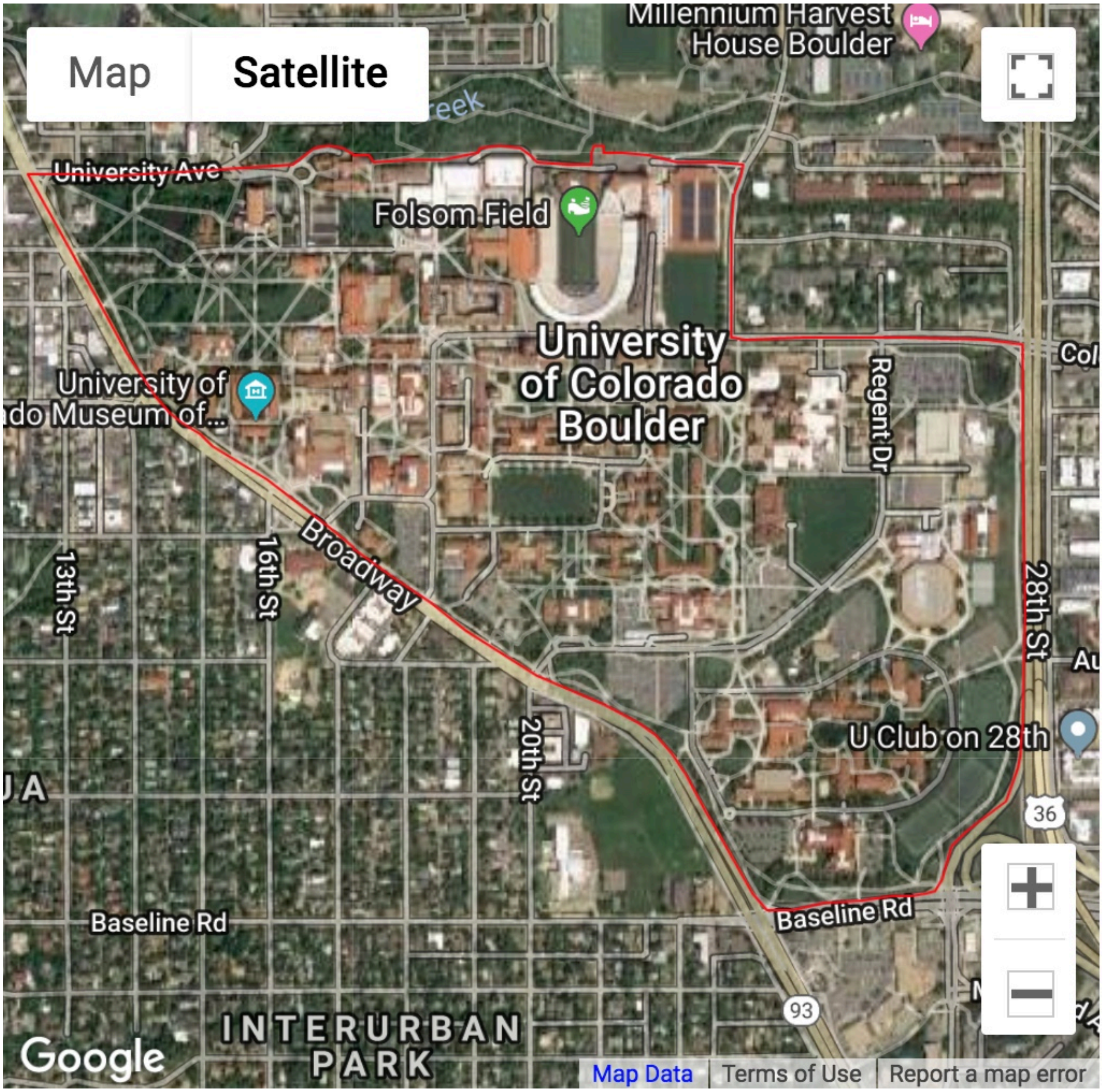

Image 4.3: The University of Colorado, Boulder Main Campus study area as defined by the red line above.

The University of Colorado, Boulder Main Campus study area is the only campus study area in this thesis. The area was chosen to act as an intermediate between highly urbanized areas and neighborhoods, and to supply the university, which is very interested in environmental planning and responsibility, with canopy cover estimates and values. The reported data will be helpful for the university to determine if the current level of canopy coverage is optimal or needs to be improved on. The study area is confined by University Avenue, 17th street, and Colorado Avenue to the north, 28th Street to the east, Baseline Road to the south, and Broadway to the west.

The University of Colorado, Boulder Main Campus' i-Tree Canopy Results:

Cover Class	Description	Abbr.	Points	% Cover
Tree	Tree, non-shrub	T	222	20.2 ±1.21
Non-Tree	All other surfaces	NT	46	4.19 ±0.61
Impermeable Surface		IS	594	54.1 ±1.50
Grass		GR	209	19.1 ±1.19
Shrub		SH	26	2.37 ±0.46

Table 4.3.1: The University of Colorado, Boulder Main Campus's estimated coverage, as reported by i-Tree Canopy, 2018.

The University of Colorado, Boulder Main Campus study area's ground coverage was calculated using the i-Tree Canopy tool. Relative percentages were determined for five ground cover types (Tree, Non-Tree, Impermeable Surface, Grass, and Shrub) through the generation of 1,097random data points within the study area. The dominant coverage type was impermeable surface area (54.1 ± 1.50%), followed by tree cover (20.2 ± 1.21%), grass cover (19.1 ± 1.19%), non-tree (dirt or gravel) cover (4.19 ± 0.61%), and shrub cover (2.37 ± 0.46%).

Tree Benefit Estimates

Abbr.	Benefit Description	Value (USD)	±SE	Amount	±SE
CO	Carbon Monoxide removed annually	34.24 USD	±2.05	51.54 lb	±3.09
NO2	Nitrogen Dioxide removed annually	199.18 USD	±11.94	606.25 lb	±36.34
O3	Ozone removed annually	3,667.72 USD	±219.85	1.36 T	±0.08
PM2.5	Particulate Matter less than 2.5 microns removed annually	1,257.57 USD	±75.38	88.75 lb	±5.32
SO2	Sulfur Dioxide removed annually	14.30 USD	±0.86	136.82 lb	±8.20
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	2,826.42 USD	±169.42	904.99 lb	±54.25
CO2seq	Carbon Dioxide sequestered annually in trees	5,861.70 USD	±351.36	166.26 T	±9.97
CO2stor	Carbon Dioxide stored in trees (Note: this benefit is not an annual rate)	228,814.45 USD	±13,715.37	6,490.20 T	±389.03

Table 4.3.2: Estimated Benefits from canopy cover in The University of Colorado, Boulder Main Campus study area, as reported by i-Tree Canopy, 2018.

The i-Tree Canopy tool used the data reported from the 1,097 randomly selected points for the University of Colorado, Boulder Main Campus study area to estimate the value (USD) of pollutant removal or sequestration performed by the trees in the study area. The highest value for annual rate of sequestration or removal was from carbon dioxide sequestered by the area's trees ($5,861.70 per year), followed by ground ozone removed (3,667.72 per year), particulate matter greater than 2.5 but less than 10 microns ($2,826.42 per year), particulate matter less than 2.5 microns ($1,257.57 per year), nitrogen dioxide removed ($199.18 per year), carbon monoxide removed ($34.24 per year), and sulfur dioxide removed ($14.30 per year). The carbon dioxide stored in University of Colorado, Boulder Main Campus study area's trees is estimated to be valued at $228,814.45 (note this is not an annual rate, but the total estimated worth of storage).

Reported Mass Converted to Metric

Pollutant (metric weight)	Current Values
CO (kg)	23.38
NO2 (kg)	274.99
O3 (T)	1.23
PM2.5 (kg)	40.26
SO2 (kg)	62.06
PM10 (kg)	410.5
CO2seq (T)	150.83
CO2stor (T)	5887.81

Table 4.3.3: The estimated mass of pollutants removed from The University of Colorado, Boulder Main Campus on a yearly basis, converted to metric units. Note that in Figure # mass was reported in English units.

THE HARLOW PLATTS/TABLE MESA NEIGHBORHOOD STUDY AREA

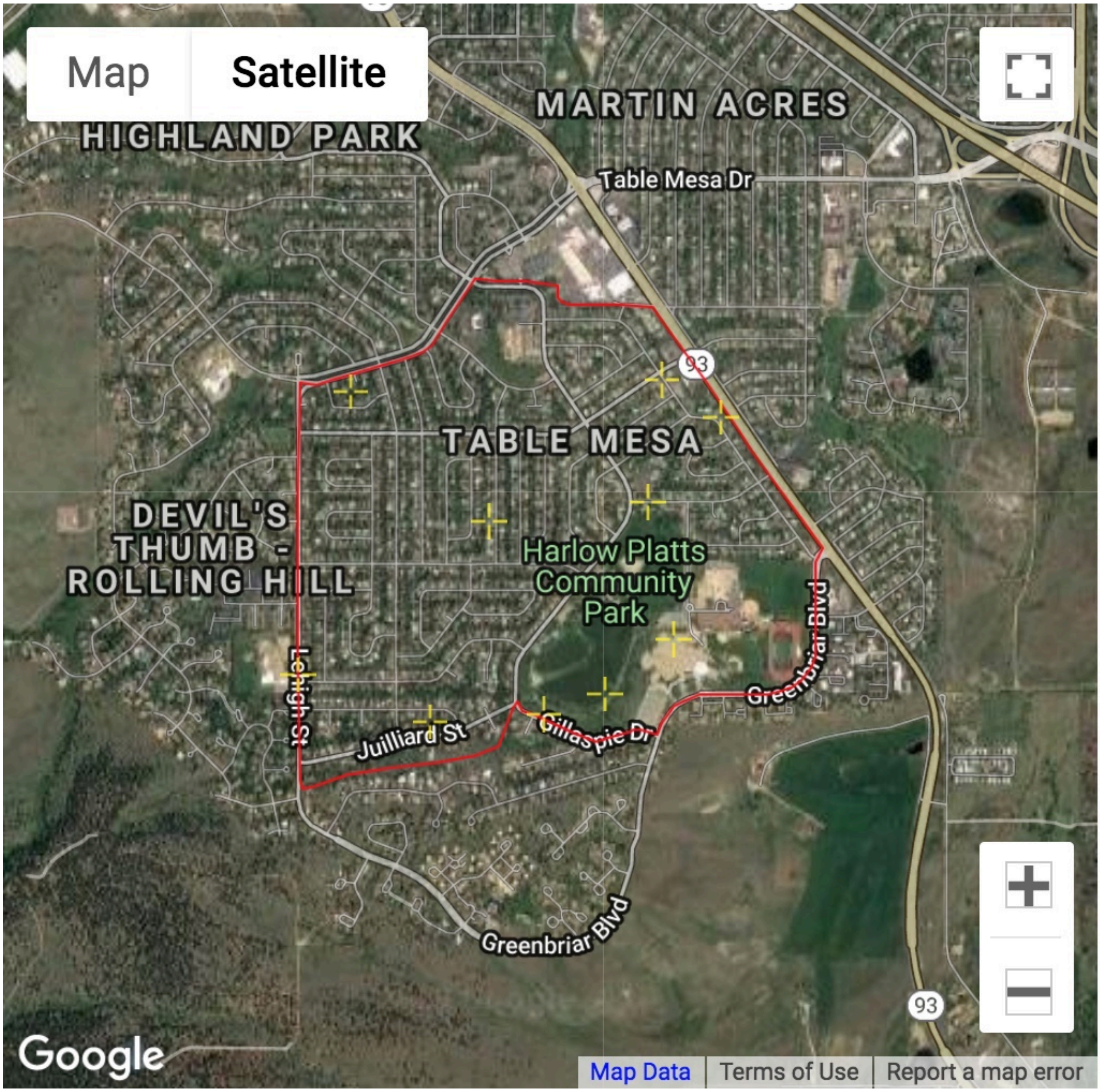

Image 4.4: The Harlow Platts/Table Mesa Neighborhood study area, as defined by the red line.

The Harlow Platts/Table Mesa Neighborhood study area is the first of three neighborhood study areas. These neighborhood areas differ from the others in that 1) they are residential areas with private properties and any data collected outside of GIS data must be collected with permission from property owners, and 2) they are characterized by higher tree, grass, and shrub coverage than the urban and university study sites. Unlike the other neighborhoods this study area features a large park, Harlow Platts Community Park, which is predominantly covered by grass. This boosts the percentage of grass coverage for the entire study area, but does not impact canopy cover. The study area is confined by Table Mesa Drive, Gillaspie Drive, Armer Avenue, and Hanover Avenue to the north, South Broadway to the east, Greenbriar Boulevard, Gillaspie Drive, and Julliard Street to the south, and Lehigh Street to the west.

HARLOW PLATTS/TABLE MESA NEIGHBORHOOD'S I-TREE CANOPY RESULTS:

Cover Class	Description	Abbr.	Points	% Cover
Tree	Tree, non-shrub	T	298	28.5 ±1.39
Non-Tree	All other surfaces	NT	91	8.69 ±0.87
Impermeable Surface		IS	403	38.5 ±1.50
Grass		GR	239	22.8 ±1.30
Shrub		SH	16	1.53 ±0.38

Table 4.4.1: Harlow Platts/Table Mesa Neighborhood's estimated coverage, as reported by i-Tree Canopy, 2018.

The Harlow Platts/Table Mesa Neighborhood study area's ground coverage was calculated using the i-Tree Canopy tool. Relative percentages were determined for five ground cover types (Tree, Non-Tree, Impermeable Surface, Grass, and Shrub) through the generation of 1,047 random data points within the study area. The dominant coverage type was impermeable surface area (38.5 ± 1.50%), followed by tree cover (28.5 ± 1.39%), grass cover (22.8 ± 1.30%), non-tree (dirt or gravel) cover (8.69 ± 0.87%), and shrub cover (1.53 ± 0.38%).

Tree Benefit Estimates

Abbr.	Benefit Description	Value (USD)	±SE	Amount	±SE
CO	Carbon Monoxide removed annually	87.99 USD	±4.31	132.44 lb	±6.49
NO2	Nitrogen Dioxide removed annually	511.84 USD	±25.08	1,557.86 lb	±76.33
O3	Ozone removed annually	9,424.85 USD	±461.78	3.49 T	±0.17
PM2.5	Particulate Matter less than 2.5 microns removed annually	3,231.55 USD	±158.33	228.05 lb	±11.17
SO2	Sulfur Dioxide removed annually	36.73 USD	±1.80	351.59 lb	±17.23
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	7,262.97 USD	±355.86	1.16 T	±0.06
CO2seq	Carbon Dioxide sequestered annually in trees	15,062.64 USD	±738.01	427.24 T	±20.93
CO2stor	Carbon Dioxide stored in trees (Note: this benefit is not an annual rate)	587,978.23 USD	±28,808.50	16,677.69 T	±817.14

Table 4.4.2: The estimated benefits (in USD) from canopy cover in the Harlow Platts/Table Mesa Neighborhood study area, as reported by i-Tree Canopy, 2018.

The i-Tree Canopy tool used the data reported from the 1,047 randomly selected points for the Harlow Platts/Table Mesa Neighborhood study area to estimate the value (USD) of pollutant removal or sequestration performed by the trees in the study area. The highest value for annual rate of sequestration or removal was from carbon dioxide sequestered by the area's trees ($15,062.64 per year), followed by ground ozone removed ($9,424.85 per year), particulate matter greater than 2.5, but less than 10 microns ($7,262.97 per year), particulate matter less than 2.5 microns ($3,231.55 per year), nitrogen dioxide removed ($511.84 per year), carbon monoxide removed ($87.99 per year), and sulfur dioxide removed ($36.73 per year). The carbon dioxide stored in the Harlow Platts/Table Mesa Neighborhood study area's trees is estimated to be valued at $587,978.23 (note this is not an annual rate, but the total estimated worth of storage).

Reported Mass Converted to Metric

Pollutant (metric weight)	Current Mass
CO (kg)	60.07
NO2 (kg)	706.63
O3 (T)	3.17
PM2.5 (kg)	103.44
SO2 (kg)	159.48
PM10 (T)	1.05
CO2seq (T)	387.59
CO2stor (T)	15129.75

Table 4.4.3: The estimated mass of pollutants removed from Harlow Platts/Table Mesa on a yearly basis, converted to metric units. Note that in Figure # mass was reported in English units.

The Aurora 7 Neighborhood Study Area

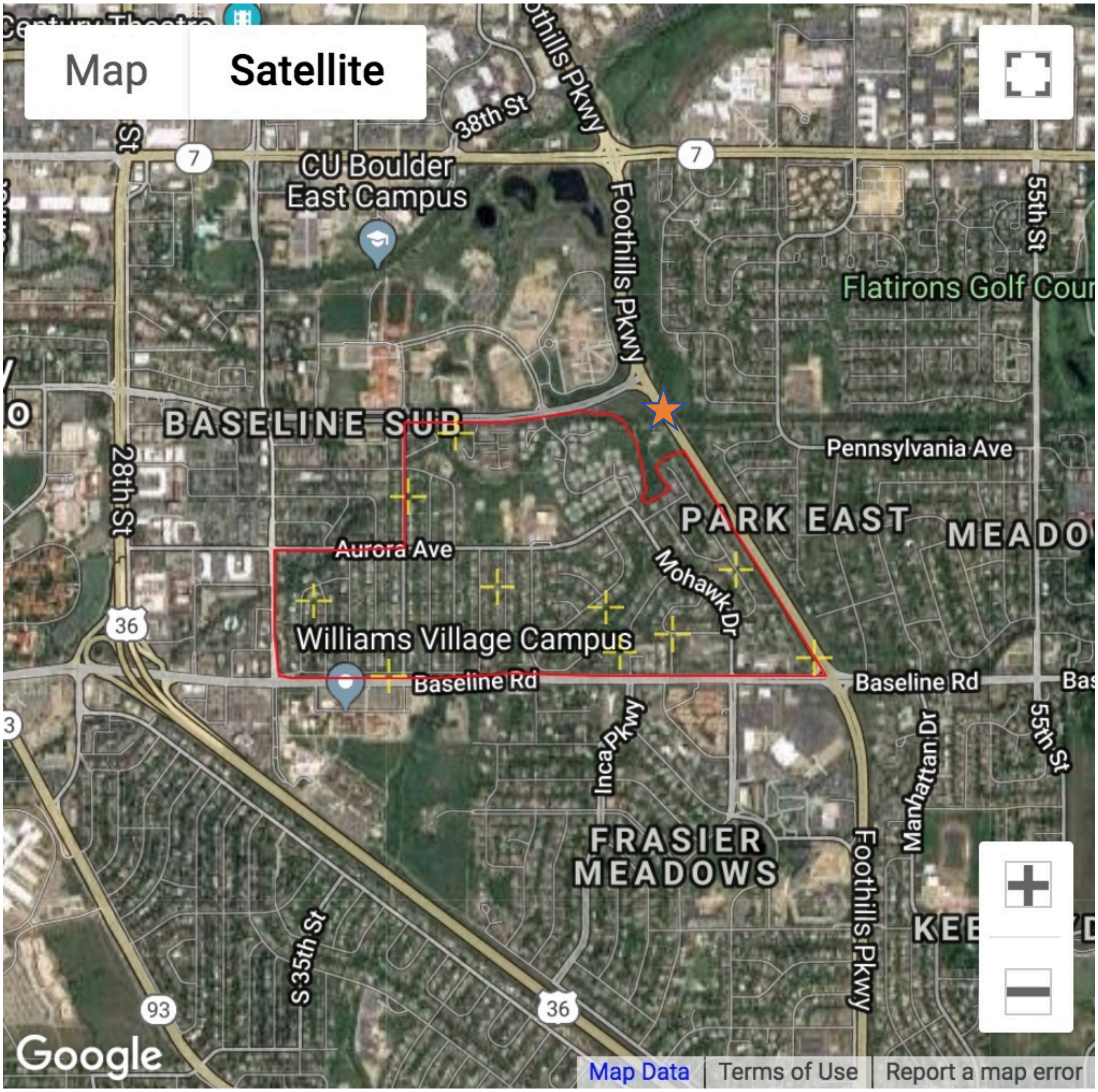

Image 4.5: The Aurora 7 Neighborhood study area, as defined by the red line.

The Aurora 7 Neighborhood study area is the second of three neighborhood study areas. The Aurora 7 Neighborhood study area is confined by Aurora Ave, 35th Street, and Colorado Avenue to the north, Foothills Parkway to the east (discounting the grass field at the corner of Foothills Parkway and Colorado Avenue, as marked by an orange star on image 4.5), Baseline Road to the south, and 30th Street to the west.

AURORA 7'S I-TREE CANOPY RESULTS:

Cover Class	Description	Abbr.	Points	% Cover
Tree	Tree, non-shrub	T	347	33.2 ±1.46
Non-Tree	All other surfaces	NT	31	2.97 ±0.53
Impermeable Surface		IS	398	38.1 ±1.50
Grass		GR	240	23.0 ±1.30
Shrub		SH	28	2.68 ±0.50

Table 4.5.1: The Aurora 7 Neighborhood study area's estimated coverage, as reported by i-Tree Canopy, 2018.

The Aurora 7 Neighborhood study area's ground coverage was calculated using the i-Tree Canopy tool. Relative percentages were determined for five ground cover types (Tree, Non-Tree, Impermeable Surface, Grass, and Shrub) through the generation of 1,044 random data points within the study area. The dominant coverage type was impermeable surface area (38.1 ± 1.50%), followed by tree cover (23.2 ± 1.46%), grass cover (23.0 ± 1.30%), non-tree (dirt or gravel) cover (2.97 ± 0.53%), and shrub cover (2.68 ± 0.50%).

Tree Benefit Estimates

Abbr.	Benefit Description	Value (USD)	±SE	Amount	±SE
CO	Carbon Monoxide removed annually	53.04 USD	±2.33	79.83 lb	±3.50
NO2	Nitrogen Dioxide removed annually	308.53 USD	±13.53	939.05 lb	±41.19
O3	Ozone removed annually	5,681.14 USD	±249.19	2.11 T	±0.09
PM2.5	Particulate Matter less than 2.5 microns removed annually	1,947.92 USD	±85.44	137.46 lb	±6.03
SO2	Sulfur Dioxide removed annually	22.14 USD	±0.97	211.93 lb	±9.30
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	4,377.99 USD	±192.03	1,401.78 lb	±61.49
CO2seq	Carbon Dioxide sequestered annually in trees	9,079.50 USD	±398.26	257.54 T	±11.30
CO2stor	Carbon Dioxide stored in trees (Note: this benefit is not an annual rate)	354,423.02 USD	±15,546.17	10,053.02 T	±440.96

Table 4.5.2: Estimated Benefits from canopy cover in The Aurora 7 Neighborhood study area, as reported by i-Tree Canopy, 2018.

The i-Tree Canopy tool used the data reported from the 1,044 randomly selected points for the Aurora 7 Neighborhood study area to estimate the value (USD) of pollutant removal or sequestration performed by the trees in the study area. The highest value for annual rate of sequestration or removal was from carbon dioxide sequestered by the area's trees ($9,079.50 per year), followed by ground ozone removed ($5,681.14 per year), particulate matter greater than

2.5, but less than 10 microns ($4,377.99 per year), particulate matter less than 2.5 microns ($1,947.92 per year), nitrogen dioxide removed ($308.53 per year), carbon monoxide removed ($53.04 per year), and sulfur dioxide removed ($22.14 per year). The carbon dioxide stored in the Aurora 7 Neighborhood study area's trees is estimated to be valued at $354,423.02 (note this is not an annual rate, but the total estimated worth of storage).

Reported Mass Converted to Metric

Pollutant (metric weight)	Current Mass
CO (kg)	36.21
NO2 (kg)	425.95
O3 (T)	1.91
PM2.5 (kg)	62.35
SO2 (kg)	96.13
PM10 (kg)	635.84
CO2seq (T)	233.64
CO2stor (T)	9119.95

Table 4.5.3: The estimated mass of pollutants removed from Aurora 7 on a yearly basis, converted to metric units. Note that in Figure # mass was reported in English units.

THE MARTIN ACRES STUDY AREA

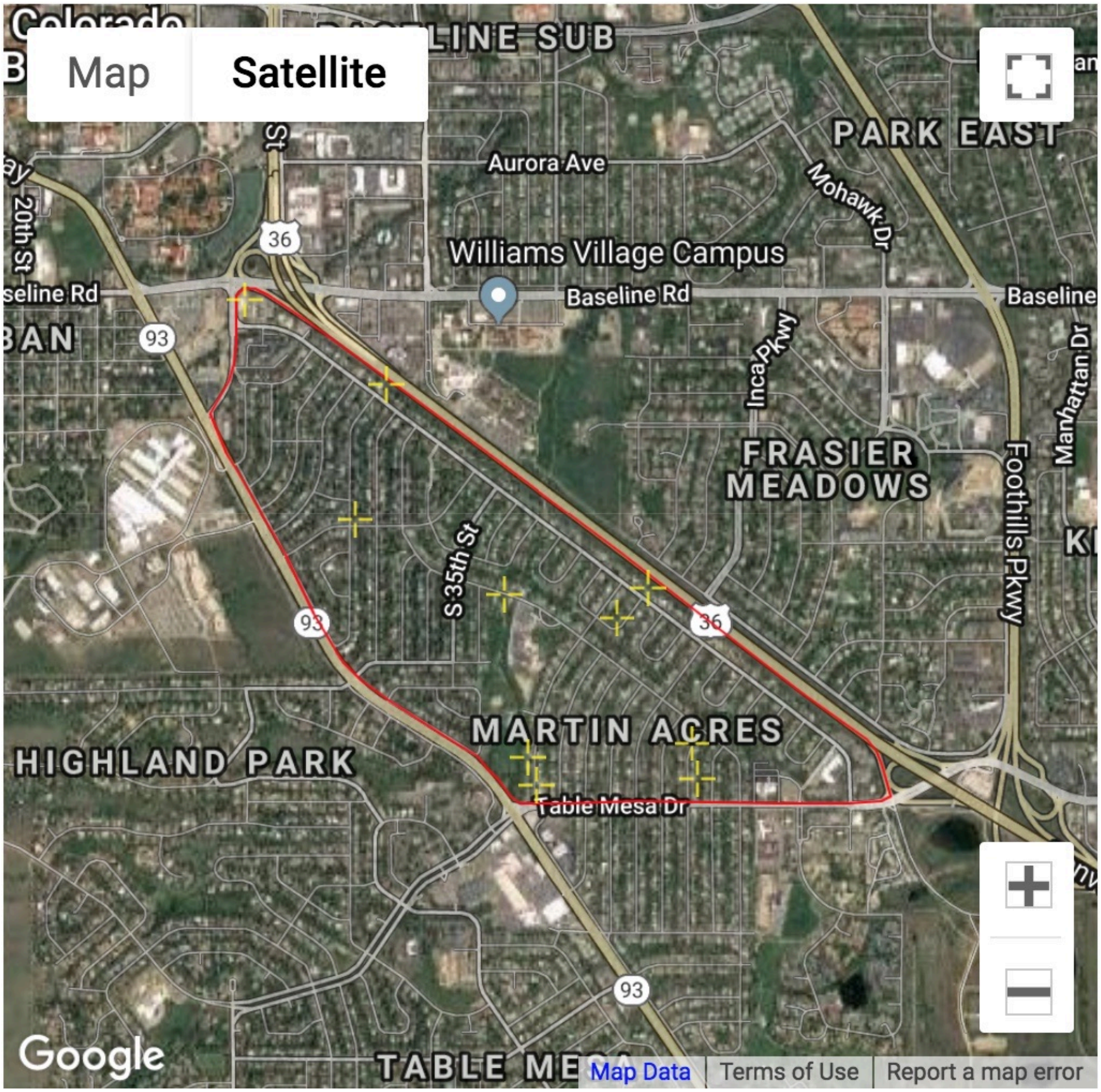

Image 4.6: The Martin Acres Neighborhood study area, as defined by the red line.

The Martin Acres Neighborhood study area is the third of three neighborhoods being studied. Like the other neighborhoods, this study area features a higher canopy cover and lower impermeable surface cover than its urban counterparts. The study area is confined by the Denver Boulder Turnpike to the northeast, Table Mesa Drive to the south, South Broadway to the southwest, and 27th Way to the northwest.

MARTIN ACRES' I-TREE CANOPY RESULTS:

Cover Class	Description	Abbr.	Points	% Cover
Tree	Tree, non-shrub	T	363	33.9 ±1.45
Non-Tree	All other surfaces	NT	35	3.27 ±0.54
Impermeable Surface		IS	441	41.2 ±1.50
Grass		GR	209	19.5 ±1.21
Shrub		SH	23	2.15 ±0.44

Table 4.6.1: The Martin Acres Neighborhood study area's estimated coverage, as reported by i-Tree Canopy, 2018.

The Martin Acres Neighborhood study area's ground coverage was calculated using the i-Tree Canopy tool. Relative percentages were determined for five ground cover types (Tree, Non-Tree, Impermeable Surface, Grass, and Shrub) through the generation of 1,071 random data points within the study area. The dominant coverage type was impermeable surface area (41.2 ± 1.50%), followed by tree cover (33.9 ± 1.45%), grass cover (19.5 ± 1.21%), non-tree (dirt or gravel) cover (3.27 ± 0.54%), and shrub cover (2.15 ± 0.44%).

Tree Benefit Estimates

Abbr.	Benefit Description	Value (USD)	±SE	Amount	±SE
CO	Carbon Monoxide removed annually	81.88 USD	±3.49	123.25 lb	±5.26
NO2	Nitrogen Dioxide removed annually	476.32 USD	±20.33	1,449.75 lb	±61.87
O3	Ozone removed annually	8,770.83 USD	±374.29	3.25 T	±0.14
PM2.5	Particulate Matter less than 2.5 microns removed annually	3,007.30 USD	±128.33	212.22 lb	±9.06
SO2	Sulfur Dioxide removed annually	34.18 USD	±1.46	327.20 lb	±13.96
PM10*	Particulate Matter greater than 2.5 microns and less than 10 microns removed annually	6,758.97 USD	±288.44	1.08 T	±0.05
CO2seq	Carbon Dioxide sequestered annually in trees	14,017.39 USD	±598.19	397.60 T	±16.97
CO2stor	Carbon Dioxide stored in trees (Note: this benefit is not an annual rate)	547,176.48 USD	±23,350.49	15,520.37 T	±662.32

Table 4.6.2: The estimated benefits (in USD) from canopy cover in the Martin Acres Neighborhood study area, as reported by i-Tree Canopy, 2018.

The i-Tree Canopy tool used the data reported from the 1,071 randomly selected points for the Martin Acres Neighborhood study area to estimate the value (USD) of pollutant removal or sequestration performed by the trees in the study area. The highest value for annual rate of sequestration or removal was from carbon dioxide sequestered by the area's trees ($14,017.39 per year), followed by ground ozone removed ($8,770.83 per year), particulate matter greater than 2.5, but less than 10 microns ($6,758.97 per year), particulate matter less than 2.5 microns ($3,007.30 per year), nitrogen dioxide removed ($476.32 per year), carbon monoxide removed ($81.88 per year), and sulfur dioxide removed ($34.18 per year). The carbon dioxide stored in the Martin Acres Neighborhood study area's trees is estimated to be valued at $547,176.48 (note this is not an annual rate, but the total estimated worth of storage).

Reported Mass Converted to Metric

Pollutant (metric weight)	Current Mass
CO (kg)	55.91
NO2 (kg)	657.6
O3 (T)	2.95
PM2.5 (kg)	96.26
SO2 (kg)	148.42
PM10 (T)	1.08
CO2seq (T)	360.7
CO2stor (T)	14079.85

Table 4.6.3: The estimated mass of pollutants removed from Martin Acres on a yearly basis, converted to metric units. Note that in Figure # mass was reported in English units.

Comparing and Contrasting the Study Areas

In order to fully understand the data that has been presented, it is important to compare and contrast data by study area and note how different coverage values impact the mass of pollutants being sequestered or stored by trees. In the following section I will describe trends in the data, focusing on differences in cover across study area types (urban versus university campus versus neighborhood). I will place special emphasis on tree and impermeable surface cover because these coverage types have a high impact on microclimates and energy use.

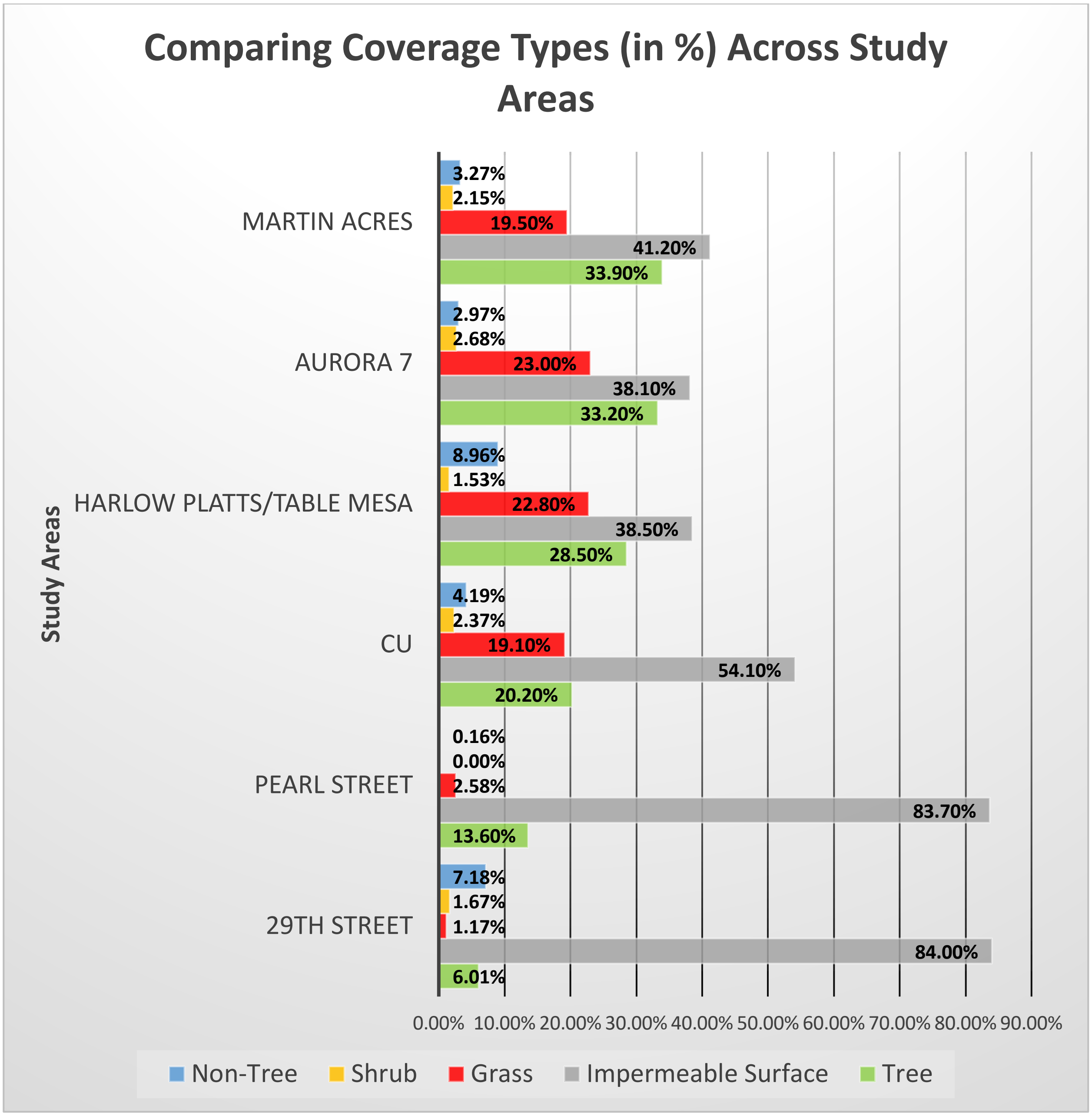

Figure 4.7.1: A graph comparing coverage types (tree, impermeable surface, grass, shrub, and non-tree) across the six study areas.

The two urban study areas (29^{th} Street Mall and Pearl Street Mall) are characterized by high impermeable surface cover (over 80%), below City of Boulder average tree cover (less than 15.9% tree cover), and extremely low presence of other coverage types (a sum of non-tree, shrub, and grass cover below 10%). 29^{th} Street Mall features both the highest impermeable surface cover (84%) and lowest tree cover (6.01%) out of all six study areas. This leaves the study area highly susceptible to infrastructure damages due to storm runoff and flooding, as well as increased heating and cooling costs due to low canopy cover and poor protection from weather extremes. Pearl Street Mall, while having over twice the canopy cover of 29th Street Mall, closely rivals 29th Street Mall in impermeable surface coverage at 83.7%. The planting of trees along the pedestrian mall helps lower energy costs from weather extremes (by providing wind breaks and shading) but does not significantly impact the amount of impermeable surface cover. Both urban areas could benefit from reducing impermeable surface cover impacts by implementing water collection or green roof technology where solar panels are not in place. In theory, impermeable surface coverage could be reduced, and grass cover could be increased by planting native grasses on their rooftops in both urban study areas.

The University of Colorado, Boulder Main Campus study area serves as an intermediate between urban and neighborhood study areas. The University's campus features an impermeable surface cover of 54.1% (about 30% less than its urban counterparts), higher than City of Boulder average tree cover at 20.2%, and rivals the neighborhood study areas in grass cover at 19.1%. Well planned landscaping of the campus has led to these differences between the campus and the two urban study areas. The campus features many grassy quadrangles and practice fields surrounded by well-established trees, areas surrounding small creeks that have large quantities of trees, and lines of trees planted within broad sidewalks to shade impermeable surfaces.

The three neighborhood study areas are characterized by around 40% impermeable surface coverage, tree cover at least 12% higher than City of Boulder average, and grass cover between 19-23%. Martin Acres features the greatest amount of tree cover (33.9%) and is closely followed by Aurora 7 (33.2%), and Harlow Platts/Table Mesa (28.5%). The three neighborhoods feature highly-forested properties with well-established trees lining their roads. Since these are suburban neighborhoods, many properties feature a high amount of grass cover for lawns and recreation spaces. In addition, the three neighborhoods generally have higher shrub and non-tree (dirt or gravel) cover than the university and urban study areas. The Harlow Platts/Table Mesa has an especially high non-tree cover (8.96%) which is due to a number of gravel/desert cover lawns which require less water to maintain (observational note from i-Tree Canopy data generation).

As hypothesized, the study area with the lowest canopy cover was in fact a highly urbanized area, 29th Street Mall (6.01% coverage), and the study area with the highest canopy coverage was a neighborhood, Martin Acres (33.9% coverage). Interestingly, these two study areas also contain the highest impermeable surface cover (29th Street Mall at 84%) and the third lowest impermeable surface cover (Martin Acres at 41.2%). Martin Acres features a canopy cover of almost six times that of 29th Street Mall as well as an impermeable surface cover over half the size of 29th Street Mall's. Based on the i-Tree Canopy data collected for these six study areas, there is a clear and demonstrable trend of low canopy/high impermeable surface cover in urban areas and high canopy/low impermeable surface cover in suburban neighborhood areas.

For further understanding of cover type layout across the study areas I have created tree cover to impermeable surface cover ratios. These ratios compare the two coverage types as proportional to each other; the closer the proportion is to 1, the more equal the two coverage types are. Ideally, tree cover would be equal to or exceed impermeable surface cover (have a proportional value close to, or greater than 1) in order to minimize impacts felt from a high impermeable surface cover (such as extreme differences between nearby microclimates, or high heat island indexes).

Tree Cover to Impermeable Surface Proportions

Study Area	Tree Cover	Impermeable Surface Cover	Tree to IS proportion
29th Street Mall	6.01%	84.00%	**0.07**
Pearl Street Mall	13.60%	83.70%	**0.16**
CU Boulder Main Campus	20.20%	54.10%	**0.37**
Harlow Platts	28.50%	38.50%	**0.74**
Aurora 7	33.20%	38.10%	**0.87**
Martin Acres	33.90%	41.20%	**0.82**

Table 4.7.2: Comparative Tree to Impermeable Surface Cover Proportions across the six study areas.

The urban study areas both fall below 0.20, giving them the lowest tree cover to impermeable surface cover proportion. Once again, The University of Colorado, Boulder Main Campus is intermediate between urban and neighborhood study areas with a proportion of 0.37. The three neighborhood study areas feature proportions above 0.70, with Aurora 7 having the highest proportion, 0.87. This is important to note, because while Martin Acres has the highest tree cover (33.9%), its higher impermeable surface cover (41.2%) makes its proportional canopy cover (0.82) lower than Aurora 7's (0.87). This highlights the importance of continuing to decrease impermeable surface cover; having higher than the City of Boulder's average tree cover does not necessarily insure that the area is minimizing the impact of its impermeable surface cover. All of the study areas can continue to reduce their impermeable surface cover by actively planting more trees, adopting green roof initiatives (like native-grass roofs), and pressuring the city to replace and maintain trees along public roads.

CHAPTER 5: IMPACTS OF THE EMERALD ASH BORER: CASE STUDIES ON TWO CITY OF BOULDER NEIGHBORHOODS

The following chapter presents and discusses case studies performed on two City of Boulder neighborhoods: Aurora 7 and Martin Acres. The neighborhoods were surveyed for the presence of ash trees on private property in order to better understand what proportion of the canopy they make up, as well as how many properties show signs of Emerald Ash Borer infestation. The City of Boulder Urban Forest Strategic Plan states that, "Even prior to the EAB detection, Boulder Forestry had begun to reduce the percent of public ash due to improve tree diversity. The overall percent of public ash decreased from 17% in 2000 to 15% in 2005 to 12% in 2013 through selective removals and diversification in replacement plantings (2018)." However, the city estimates that ash trees currently make up about 25% of Boulder's urban canopy (~12% on private property, and ~12% on public property). These neighborhood surveys were designed to investigate ash tree densities and potential loss from infestation on private lands, where City of Boulder Forestry does not have jurisdiction. Here, I present my findings, determine if the study areas are statistically similar to one another, and discuss whether or not these two neighborhoods are representative of neighborhoods throughout the city.

BACKGROUND INFORMATION ON THE EMERALD ASH BORER

The US infestation of Emerald Ash Borer (*Agrilus planipennis*) was first detected in Detroit, Michigan in 2002. The beetle, native to central and southeast Asia, likely travelled to Detroit via wooden shipping crates, a well-known source of invasive forest pests. These pests feed on white and green ash trees (*Fraxinus americana and Fraxinus pennsylvanica,* respectively*)*, causing both aesthetic and internal damage to the trees. Aesthetic damage is caused by both adults and larvae, though effects of larval feeding can take from five to ten years to show (Poland and McCullough, 2006). The adults feed on buds and leaves of the ash trees while larvae tunnel through the soft phloem and cambium tissue (vascular tissues that transport water and nutrients throughout the tree) that lie beneath the tree's hard outer bark. Serpentine-shaped larval galleries inside the tree can cause what is called a "girdling effect," which occurs when the larvae create a gallery that encompasses the entire circumference of the tree. When the phloem and/or cambium tissue are damaged in this manner, circulation in the tree is cut off, acting like a larvae-made tourniquet which causes tree death in one to three years (Cappaert et al., 2005).

Adult Emerald Ash Borers (EAB) emerge from ash trees through characteristic D-shape exit holes and are ready to fly directly after exit. The adult males feed for five to seven days after exiting the tree and then begin to breed while the females need an additional five to seven days (ten to fourteen days total) to feed before breeding. EAB continue to feed and breed for the remaining three to six weeks of their life with a single female beetle laying between 50 and 90 eggs during this time (Bauer et al., 2004). These eggs, deposited in bark crevices, usually hatch within two weeks with the newly hatched larvae immediately burrowing into the sensitive inner tissues of the tree. The larvae continue to feed through October and overwinter in their galleries finally emerging as adults in mid-April of the following year (Cappaert et al., 2005).

Signs of Infestation

The telltale signs of Emerald Ash Borer infestation include but are not limited to: D-shaped exit holes left by adult beetles, horizontal cracks in the outer bark (usually occurring over larval galleries), canopy dieback, and epicormic shoots (new shoot/branch growth occurring below older, active shoots and branches--usually due to branch and shoot damage higher up in the tree) near the base of the trunk or on larger branches (see appendix 2 for examples).

However, dendrochronology studies conducted on infested ash trees inform us that there is an average lag time of ten years before outward signs of infestation manifest (Poland and McCullough, 2006). In order to overcome this set back, foresters must use other methods to identify infestation. To date, the best method of detection is a practice called "branch sampling," first introduced to forestry management by the Canadian Forest Service. As its name implies, this method works by removing two branches (2-6 inches in diameter) from the middle of the southern facing crown of an ash tree. The forester then examines these branches for signs of D-shaped exit holes and larval galleries (Boulder County Emerald Ash Borer Management Plan, 2015). This method, while not perfect, is preferred because no harm comes to the trunk of the tree and foresters can detect early signs of infestation from crown branches where EAB infestations typically begin.

Boulder County Infestation

The Emerald Ash Borer was first discovered in the City of Boulder in 2013, the westernmost infestation site to date. In November of the same year, Boulder County was put under quarantine as mandated by the state of Colorado. Since processed lumber types can prove hard to tell apart, the quarantine restricted the movement of all non-pine lumber into and out of the quarantine zone, including but not limited to: firewood, woodchips and mulch, nursery stock, and branches (Boulder County Emerald Ash Borer Management Plan, 2015).

Ash trees make up an estimated 12% of the City of Boulder's public trees and are thought to make up a similar proportion (12%) of private trees. The current infestation of Emerald Ash Borers is projected to decimate up to 25% of Boulder's urban forest by 2023. Emerald Ash

Borers are known to travel up to 6 miles in a lifetime, making their natural spreading speed fairly slow. However, their ability to live undetected for up to a decade, as well as being transported by infested building materials, shipping crates, and firewood, make it difficult to determine the exact size of an infested area (City of Boulder Urban Forest Strategic Plan, 2018). The city must grapple not only with the potential for great canopy loss but must also consider what is necessary to limit the western expansion of the infestation.

The Aurora 7 Ash Tree Study

There is very little historical information on the Aurora 7 neighborhood. From what I have gathered, the neighborhood park was named after the astronaut Scott Carpenter, and the neighborhood's school (founded 1964) was named after his capsule on the Mercury 7 mission- Aurora 7. The neighborhood was built in the early 60's, with original homes still standing today (Snider, 2012).

The Aurora 7 ash tree study occurred on Saturday, February 9, 2019 between the hours of 1pm and 5pm. Five trained volunteers (including myself) set out to survey the neighborhood. 186 of the 750 total properties in the neighborhood were visited (about 25%) and 87 (about 47% of visited properties) participated in our survey. We found that, overall, the neighborhood had a low proportion of ash to non-ash trees in its canopy, with only 6.4% of trees on surveyed properties being ash. Of the properties surveyed, only 5 (6%) showed signs of Emerald Ash Borer Infestation. On average, each property housed 6.5 trees with 0.5 of these being ash trees. Volunteers reported that many residents of the neighborhood were renters, and that they tended to find ash trees more commonly on rental properties than permanent residences. While this is an interesting observational note, I did not plan on collecting this kind of demographic data, and it was not officially recorded in our data set. Another study would need to be conducted to explore the difference in ash densities between rental and permanent resident properties.

Results from the Aurora 7 Ash Tree Survey

Category	Totals
Total properties in study area	750
Properties visited	186 (~25% of total properties)
Properties where residents answered	92 (~50% of visited properties)
# of properties that gave permission to check yards	87 (~47% of visited properties)
Total trees surveyed	584 (548 non-ash trees)
Total ash trees surveyed	36
% ash trees on surveyed properties	6.4%
Average (standard Deviation) # of trees per property surveyed	6.7 (7.8)
Average (mean) # of ash trees per property surveyed	0.5 (1.4)
Total surveyed properties with signs of EAB	5
% surveyed properties with signs of EAB	6%

Table 5.2.1: Results from a survey of properties in the Aurora 7 Neighborhood study area. 186 properties (~25% of total properties) were randomly selected to be surveyed out of 751 total properties in the study area. Of these 186 properties, 87 yielded data (~12% of total properties).

The Martin Acres Ash Tree Study

Originally historic Martin Farm land, the Martin Acres neighborhood was founded in 1954 in order to accommodate the booming population of post WWII Boulder, Colorado. Construction on the neighborhood began shortly after the completion of the Denver-Boulder Turnpike in 1952. The neighborhood initially served as housing for employees of Rocky Flats Nuclear Weapons Factory, Dow Chemical, the University of Colorado, and the new booming aerospace industry (History of Boulder, Bryant and Schomig, 2010). As is the case in most of Boulder, the area had very few trees when the neighborhood was established, with the exception of fruit trees planted on the old Martin Farm. As the farmland grew into a suburban neighborhood there was an increased demand for tree planting, which led to the urban canopy we see today.

The Martin Acres ash tree survey occurred on Sunday, February 10, 2019 between the hours of 1pm and 5pm. Four trained volunteers (including myself) set out to survey the neighborhood for ash trees on private property. It is important to note that I had planned to have six volunteers on this day, rather than four. In order to insure the safety of our volunteers, I had been sending them out in pairs. Due to having fewer volunteers than anticipated, we were only able to survey two of the three planned routes which resulted in a smaller sample size than I had intended. However, surveyors managed to visit 129 properties (about 10% of total properties in the neighborhood) and were able to survey 56 (about 43% of visited properties) of them. From these properties we found that only 5% of the neighborhood's canopy contained ash trees. However, 12.5% of surveyed properties showed identifiable signs of Emerald Ash Borer Infestation. Each property featured an average of 8.4 trees with 0.4 of these trees being ash.

Results from the Martin Acres Ash Tree Survey

Category	Totals
Total properties in study area	1346
Properties visited	129 (~10% total of properties)
Properties where residents answered	70 (~54% of visited properties)
# of properties that gave permission to check yards	56 (~43% of visited properties)
Total Trees surveyed	470 (447 non-ash trees)
Total ash trees surveyed	23
% ash trees on surveyed properties	5%
Average (standard deviation) # of trees per property surveyed	8.1 (4.9)
Average (standard deviation) # of ash trees per property surveyed	0.4 (1.0)
Total surveyed properties with signs of EAB	7
% surveyed properties with signs of EAB	12.5%

Table 5.3.1: Results from a survey of properties in the Martin Acres Neighborhood study area. 129 properties (~10% of total properties) were randomly selected to be surveyed out of 1346 total properties in the study area. Of these 129 properties, 56 yielded data (~4.2% of total properties).

DISCUSSION OF CASE STUDIES

These case studies are important snapshots of information about two Boulder neighborhoods. However, I do not think that these studies are representative of The City of Boulder's neighborhoods overall. In both neighborhoods, surveyors noted that permanent residents were well informed on issues surrounding ash trees and the Emerald Ash Borer, often being able to inform volunteers which trees on their property were ash and where other ash trees were on their block. The high education level among residents regarding Emerald Ash Borers could contribute to why ash trees made up such a low percentage of these neighborhoods' canopies.

Aurora 7 seemed to have more renters than permanent residents, which may account for the 1.4% difference in ash tree density between the two study areas (Aurora 7 had 6.43% ash, and Martin Acres had 5% ash). Surveyors observed that it was more common to find ash trees (especially infested ash trees) on rental properties with renters often being unaware that they had an ash tree or that the tree was infested and potentially unsound. This raises the question of whether or not landlords are being held accountable for tree care and maintenance on their leased properties- a question that cannot be properly answered with my current dataset and requires more research over a greater set of study areas.

In order to assess whether or not these two study areas are statistically comparable, I ran four T-tests in excel; the first compared the number of trees per property, the second compared the number of ash trees per property overall, the third compared the number of ash trees per property with ash trees present (removing properties without ash from the datasets), and the final T-test compared the number of properties with signs of Emerald Ash Borer infestation. All four T-tests were conducted as two-sample with assumed unequal variances in order to account for differences in number of data points collected per study area. Discussion of the results will focus on two-tail p-values in order to account for variations on both ends of the datasets. For each of the four T-tests I sought to support one of the following hypotheses: H_o (null): The two study areas are statistically similar to one another ($p > 0.05$), and H_a (alternative): The two areas are not statistically similar to each other ($p < 0.05$).

T-test 1: Comparing Trees per Property

Trees per Property	Aurora 7	Martin Acres
Mean	6.71	8.10
Variance	60.42	24.20
Observations	87.00	58.00
Hypothesized Mean Difference	0.00	
df	143.00	
t Stat	-1.32	
P(T<=t) one-tail	0.09	
t Critical one-tail	1.66	
P(T<=t) two-tail	0.19	
t Critical two-tail	1.98	
Aurora 7 Standard Deviation	7.77	
Martin Acres Standard Deviation	4.92	

Table 5.4.1: This table shows results from a T-test run on "trees per property" datasets from Aurora 7 and Martin Acres.

The first T-test (see table 5.4.1) compared case study data regarding the number of trees per property across both study sites. The T-test showed that Martin Acres has a higher average number of trees per property (8.10) compared to Aurora 7 (6.71), with more variation in Aurora 7 (standard deviation of 7.77, compared to 4.92 in Martin Acres). This difference in variance between the two study areas is likely due to a single outlying data point in the Aurora 7 dataset. This outlier was a large property that encompassed a section of the creekbank and contained 64 trees, 7 of which were ash. The Aurora 7 outlier accounts for the significantly higher standard deviation and likely skewed the mean. When the outlier is removed from the Aurora 7 dataset, the mean number of trees per property shrinks to 6.05 and the standard deviation becomes 4.70. Outliers are important to consider because they may be more frequent in the true population. However, even including the Aurora 7 outlier this T-test supports the null hypothesis with a p-value of greater than 0.05 ($p = 0.19$), implying that the two study areas are indeed statistically similar regarding the average number of trees per property.

T-test 2: Comparing Ash Trees per Property

Ash Trees per Property (All Properties)	*Aurora 7*	*Martin Acres*
Mean	0.45	0.40
Variance	1.88	1.05
Observations	87.00	58.00
Hypothesized Mean Difference	0.10	
df	141.00	
t Stat	-0.24	
P(T<=t) one-tail	0.40	
t Critical one-tail	1.66	
P(T<=t) two-tail	0.81	
t Critical two-tail	1.98	
Aurora 7 Standard Deviation	1.37	
Martin Acres Standard Deviation	1.02	

Table 5.4.2: This table shows results from a T-test run on "ash trees per property" datasets from Aurora 7 and Martin Acres.

The second T-test examined statistical similarities or differences between the average number of ash trees per property across the Aurora 7 and Martin Acres datasets. While the means of the two were fairly similar (0.45 for Aurora 7, and 0.40 for Martin Acres), the variance was notably different as it was for T-test 1 (standard deviation of 1.37 for Aurora 7, 1.02 for Martin Acres). However, when the Aurora 7 outlier is removed from the dataset, Aurora 7's mean number of ash trees per property falls to 0.37, and the standard deviation shifts to 1.18. This shows that the Aurora 7 outlier skews the mean by 0.08 ash trees per property and inflates the standard deviation by 0.19. T-test 2 once again supports the null hypothesis that the two study areas are statistically similar regarding the number of ash trees per property with a high p-value of 0.81.

T-test 3: Comparing Number of Ash Trees on Properties with Ash Present

Ash Count on Properties with Ash Trees	*Aurora 7*	*Martin Acres*
Mean	1.95	1.77
Variance	5.42	2.36
Observations	20.00	13.00
Hypothesized Mean Difference	0.00	
df	31.00	
t Stat	0.27	
P(T<=t) one-tail	0.39	
t Critical one-tail	1.70	
P(T<=t) two-tail	0.79	
t Critical two-tail	2.04	
Aurora 7 Standard Deviation	2.33	
Martin Acres Standard Deviation	1.54	

Table 5.4.3: This table shows results from a T-test run on "number of ash trees on properties with ash" datasets from Aurora 7 and Martin Acres.

The third T-test was run in addition to the second T-test in order to refine results by only examining properties with ash trees present, which effectively removed values of zero from the dataset. This creates another set of averages separate from the entire dataset's average number of ash trees per property. Only considering properties with ash trees present, the average number of ash trees per property in Aurora 7 is 1.95, and 1.77 for Martin Acres, with standard deviations of 2.33 and 1.54, respectively. Without the Aurora 7 outlier, which contains 7 ash trees, Aurora 7's mean drops to 1.68 ash trees per property, and the standard deviation falls to 2.06. The p-value for this T-test (0.79) once again supports the null hypothesis, that the two study areas are statistically similar to one another.

T-test 4: Comparing Number of Properties with Signs of Infestation

Infestation on Properties with Ash Trees	Aurora 7	Martin Acres
Mean	0.25	0.54
Variance	0.20	0.27
Observations	20.00	13.00
Hypothesized Mean Difference	0.00	
df	23.00	
t Stat	-1.65	
P(T<=t) one-tail	0.06	
t Critical one-tail	1.71	
P(T<=t) two-tail	0.11	
t Critical two-tail	2.07	
Aurora 7 Standard Deviation	0.44	
Martin Acres Standard Deviation	0.52	

Table 5.4.4: This table shows results from a T-test run on "properties with signs of infestation" datasets from Aurora 7 and Martin Acres.

The fourth T-test compared the number of properties containing ash trees with signs of Emerald Ash Borer infestation across the two datasets. As in T-test 3, this test only examines properties with ash trees present in order to refine results. The results show that Martin Acres has an average of about twice the amount of infested properties (0.54, versus 0.25 in Aurora 7)) as, and a higher standard deviation (0.52, versus 0.44) than, Aurora 7. Since this scenario only considers the presence of infestation, rather than the quantity of infested trees, the impact of the Aurora 7 outlier will not be examined in this statistical analysis. This T-test, as in the other three, supports the null hypothesis that these two study areas are statistically similar, with a non-significant p-vale of 0.11.

Based on all four T-tests, these two areas are statistically similar (null hypothesis confirmed). This finding affirms the notion that Boulder neighborhoods within a short distance from each other (in this case about 3.5 miles apart) can be treated as similar scenarios with comparable environmental factors and considerations. However, it is important to note that this may not be the case for neighborhoods a greater distance from one another. It is likely that as compared neighborhoods become further apart that they become statistically different from each other ($p < 0.05$) due to differences in environmental conditions, neighborhood layout, and residential affluence. Further studies would need to be conducted with a larger sampling of neighborhoods from different regions of the city and different levels of income in order to assess the validity of this assumption. Differences between means from the final T-test (table 5.4.4) could indicate that while the two neighborhoods are similar in distribution of total trees and ash trees per property, Aurora 7 may be treating ash trees for Emerald Ash Borers more regularly, resulting in a lower rate of infested properties than Martin Acres.

Interestingly, both neighborhoods have significantly lower ash tree densities than estimated by the city (12% private tree cover). Survey results found that Aurora 7 has only about 6.4% ash tree cover, and Martin Acres has only 5%. It is possible that these low percentages are reflective of the level of emerald ash borer awareness in the residents of these neighborhoods. Areas that have been targeted with ash tree educational materials and programs (as both Aurora 7 and Martin Acres have) are more likely to have lower ash tree densities than uneducated areas because informed residents will sooner consider ash tree removal.

In order to get a better estimate of the true population mean, it would be necessary to conduct multiple data samplings in the same areas. The two datasets and related T-tests simply showcase similarities and differences between two distinct study areas. The fact of the matter is that these two case studies only examined upper-class, well-educated neighborhoods with the means to dispose of or treat infested trees. Future studies should focus on understanding differences between low income and high-income neighborhoods, as well as differences between rental properties and permanent residences. I would also suggest that i-Tree Canopy be used with historical maps to examine canopy cover before the Emerald Ash Borer was discovered in the city and compare this to my current dataset. I feel that with this information one could examine how high versus low income neighborhoods responded to information regarding the infestation by tracking canopy density changes over time.

CHAPTER 6: AN ASSESSMENT OF FUTURE SCENARIOS: EXPLORING 2%, 4%, AND 10% INCREASES TO CANOPY COVER

The following chapter deals with scenarios of canopy increase across the six study areas. While the City of Boulder's current urban canopy goals are based on maintaining 16% canopy coverage (City of Boulder Urban Forest Strategic Plan, 2018), I have chosen three increase scenarios to explore; a "mild" increase of 2%, a "moderate" increase of 4%, and a "difficult" increase of 10%.

First, I will focus on sequestering, removal, and storage potentials in terms of mass if each study area were to increase their canopy cover by 2%, 4%, and 10%. These estimated increases are a direct function of the current estimated masses and economic value of sequestered, removed, or stored pollutants. Since the i-Tree Canopy modeling system determines sequestration values based on an area of tree canopy to area of study site ratio, it is appropriate to simply find the value of 2%, 4%, or 10% of these masses and economic values and add them to the current estimated values. Mass and economic potential for 2%, 4%, or 10% canopy increases are reported as what could be gained *in addition to* the current mass and value of sequestered materials for each study area.

The second section of this chapter will report changes in tree cover to impermeable surface cover ratios when under these increase scenarios. It is important to note that these proportional changes assume that *increases in canopy cover result in an equal decrease in impermeable surface cover.* In other words, I assume that newly established tree canopies will cover existing impermeable surfaces.

The final section of this chapter will be a discussion of the data reported in the first two sections. Here, I will discuss the relevance and importance of increasing canopy cover as applies to the six study areas and the achievability of these increase scenarios.

Increasing Tree Cover and Changes to Sequestered or Removed Pollutants By Study Area (Data Report)

The following subsections will report the potential mass of sequestered materials under canopy increase scenarios (increase 2%, 4%, and 10%) for each of the six study areas. These estimates demonstrate the value of increasing canopy cover in terms of pollutants removed from the atmosphere. I will also report the estimated economic value of these increase scenarios in 2018 USD. Both mass and economic value estimates are based on data extrapolations from the previously discussed 2018 i-Tree Canopy reports (see chapter 4).

29th Street Mall

Recall from subsection 4.1 that 29th Street Mall has the least amount of canopy cover (6.01%) and the highest impermeable surface cover (84%) of all six study areas. The 2%, 4%, and 10% increase scenarios would bring 29th Street Mall's canopy cover up to 8.01%, 10.01%, and 16.01%, respectively, and the mall's impermeable surface cover down to 82%, 80%, and 74%, respectively. The following tables report additional mass and economic value that would be gained under 2%, 4%, and 10% increase scenarios.

Additional Mass Sequestered Under Increase Scenarios: 29th Street Mall

Pollutant (metric weight)	Current Mass	2% Increase	4% Increase	10% Increase
CO (kg)	2.46	0.05	0.10	0.25
NO2 (kg)	28.97	0.58	1.16	2.90
O3 (kg)	129.90	2.60	5.20	12.99
PM2.5 (kg)	4.24	0.08	0.17	0.42
SO2 (kg)	6.54	0.13	0.26	0.65
PM10 (kg)	43.25	0.87	1.73	4.33
CO2seq (T)	15.89	0.32	0.64	1.59
CO2stor (T)	620.31	12.41	24.81	62.03

Table 6.1.1: Illustrates additional mass of sequestered, removed, or stored pollutants when tree cover increases by 2%, 4%, and 10% in the 29th Street Mall study area.

Additional Economic Value Under Increase Scenarios: 29th Street Mall

Pollutants	Current Values (USD)	2% increase	4% increase	10% increase
CO	$3.61	$0.07	$0.14	$0.36
NO2	$20.99	$0.42	$0.84	$2.10
O3	$386.42	$7.73	$15.46	$38.64
PM2.5	$132.49	$2.65	$5.30	$13.25
SO2	$1.51	$0.03	$0.06	$0.15
PM10	$297.78	$5.96	$11.91	$29.78
CO2seq	$617.56	$12.35	$24.70	$61.76
CO2stor	$24,106.90	$482.14	$964.28	$2,410.69

Table 6.1.2: This table shows current values of pollutant removal (in 2018 USD) and estimates for additional value if the 29th Street Mall study area were to increase its canopy coverage by 2%, 4%, and 10%.

PEARL STREET MALL

In subsection 4.2 we saw that Pearl Street Mall has the second smallest canopy coverage (13.6%) and the second highest impermeable surface cover (83.7%) of the six study areas. The 2%, 4%, and 10% increase scenarios would bring Pearl Street Mall's canopy cover up to 15.6%, 17.6%, and 23.6%, respectively, and the mall's impermeable surface cover down to 81.7%, 79.7%, and 73.7%, respectively. The following tables report additional mass and economic value that would be gained under 2%, 4%, and 10% increase scenarios.

Additional Mass Sequestered Under Increase Scenarios: Pearl Street Mall

Pollutant (metric weight)	Current Values	2% Increase	4% Increase	10% Increase
CO (kg)	6.99	0.14	0.28	0.70
NO2 (kg)	82.25	1.65	3.29	8.23
O3 (kg)	368.75	7.38	14.75	36.88
PM2.5 (kg)	12.04	0.24	0.48	1.20
SO2 (kg)	18.56	0.37	0.74	1.86
PM10 (kg)	122.77	2.46	4.91	12.28
CO2seq (T)	45.11	0.90	1.80	4.51
CO2stor (T)	1760.95	35.22	70.44	176.10

Table 6.1.3: Illustrates additional mass of sequestered, removed, or stored pollutants when tree cover increases by 2%, 4%, and 10% in the Pearl Street Mall study area.

Additional Economic Value Under Increase Scenarios: Pearl Street Mall

Pollutants	Current Values (USD)	2% increase	4% increase	10% increase
CO	$10.24	$0.20	$0.41	$1.02
NO2	$59.57	$1.19	$2.38	$5.96
O3	$1,096.95	$21.94	$43.88	$109.70
PM2.5	$376.12	$7.52	$15.04	$37.61
SO2	$4.28	$0.09	$0.17	$0.43
PM10	$845.33	$16.91	$33.81	$84.53
CO2seq	$1,753.13	$35.06	$70.13	$175.31
CO2stor	$68,434.52	$1,368.69	$2,737.38	$6,843.45

Table 6.1.4: This table shows current values of pollutant removal (in 2018 USD) and estimates for additional value if the Pearl Street Mall study area were to increase its canopy coverage by 2%, 4%, and 10%.

THE UNIVERSITY OF COLORADO, BOULDER MAIN CAMPUS

In subsection 4.3 we saw that The University of Colorado, Boulder Main Campus study area is intermediate in cover proportions between urban areas and neighborhood areas with a canopy cover of 20.2% and an impermeable surface cover of 54.1%. The 2%, 4%, and 10% increase scenarios would bring CU, Boulder Main Campus' canopy cover up to 22.2%, 24.2%, and 30.2%, respectively, and the campus' impermeable surface cover down to 52.1%, 50.1%, and 44.1%, respectively. The following tables report additional mass and economic value that would be gained under 2%, 4%, and 10% increase scenarios.

Additional Mass Sequestered Under Increase Scenarios: CU, Boulder Main Campus

Pollutant (metric weight)	Current Values	2% Increase	4% Increase	10% Increase
CO (kg)	23.38	0.47	0.94	2.34
NO2 (kg)	274.99	5.50	11.00	27.50
O3 (T)	1.23	0.02	0.05	0.12
PM2.5 (kg)	40.26	0.81	1.61	4.03
SO2 (kg)	62.06	1.24	2.48	6.21
PM10 (kg)	410.50	8.21	16.42	41.05
CO2seq (T)	150.83	3.02	6.03	15.08
CO2stor (T)	5887.81	117.76	235.51	588.78

Table 6.1.5: Illustrates additional mass of sequestered, removed, or stored pollutants when tree cover increases by 2%, 4%, and 10% in The University of Colorado, Boulder Main Campus study area.

Additional Economic Value Under Increase Scenarios: CU, Boulder Main Campus

Pollutants	Current Values (USD)	2% increase	4% increase	10% increase
CO	$34.24	$0.68	$1.37	$3.42
NO2	$199.18	$3.98	$7.97	$19.92
O3	$3,667.72	$73.35	$146.71	$366.77
PM2.5	$1,257.57	$25.15	$50.30	$125.76
SO2	$14.30	$0.29	$0.57	$1.43
PM10	$2,826.42	$56.53	$113.06	$282.64
CO2seq	$5,861.70	$117.23	$234.47	$586.17
CO2stor	$228,814.45	$4,576.29	$9,152.58	$22,881.45

Table 6.1.6: This table shows current values of pollutant removal (in 2018 USD) and estimates for additional value if The University of Colorado, Boulder Main Campus study area were to increase its canopy coverage by 2%, 4%, and 10%.

Harlow Platts/Table Mesa Neighborhood

Recall that in subsection 4.4 it was demonstrated that the Harlow Platts/Table Mesa neighborhood study area had the lowest canopy cover of the three neighborhood study areas (28.5%), and fairly low impermeable surface coverage (38.5%). The 2%, 4%, and 10% increase scenarios would bring Harlow Platts/Table Mesa's canopy cover up to 30.5%, 32.5%, and 38.5%, respectively, and the neighborhood's impermeable surface cover down to 36.5%, 34.5%, and 28.5%, respectively. The following tables report additional mass and economic value that would be gained under 2%, 4%, and 10% increase scenarios.

Additional Mass Sequestered Under Increase Scenarios: Harlow Platts/Table Mesa

Pollutant (metric weight)	Current Mass	2% Increase	4% Increase	10% Increase
CO (kg)	60.07	1.20	2.40	6.01
NO2 (kg)	706.63	14.13	28.27	70.66
O3 (T)	3.17	0.06	0.13	0.32
PM2.5 (kg)	103.44	2.07	4.14	10.34
SO2 (kg)	159.48	3.19	6.38	15.95
PM10 (T)	1.05	0.02	0.04	0.11
CO2seq (T)	387.59	7.75	15.50	38.76
CO2stor (T)	15129.75	302.60	605.19	1512.98

Table 6.1.7: Illustrates additional mass of sequestered, removed, or stored pollutants when tree cover increases by 2%, 4%, and 10% in Harlow Platts/Table Mesa Neighborhood study area.

Additional Economic Value Under Increase Scenarios: Harlow Platts/Table Mesa

Pollutants	Current Values (USD)	2% increase	4% increase	10% increase
CO	$87.99	$1.76	$3.52	$8.80
NO2	$511.84	$10.24	$20.47	$51.18
O3	$9,424.85	$188.50	$376.99	$942.49
PM2.5	$3,231.55	$64.63	$129.26	$323.16
SO2	$36.73	$0.73	$1.47	$ 3.67
PM10	$7,262.97	$145.26	$290.52	$726.30
CO2seq	$15,062.64	$301.25	$602.51	$1,506.26
CO2stor	$587,978.23	$11,759.56	$23,519.13	$58,797.82

Table 6.1.8: This table shows current values of pollutant removal (in 2018 USD) and estimates for additional value if the Harlow Platts/Table Mesa Neighborhood study area were to increase its canopy coverage by 2%, 4%, and 10%.

Aurora 7 Neighborhood

As discussed in subsection 4.5, the Aurora 7 neighborhood study area's canopy cover was 33.2%, and its impermeable surface cover was 38.1%. The 2%, 4%, and 10% increase scenarios would bring Aurora 7's canopy cover up to 35.2%, 37.2%, and 43.2%, respectively, and the neighborhood's impermeable surface cover down to 36.1%, 34.1 %, and 28.1 %, respectively. The following tables report additional mass and economic value that would be gained under 2%, 4%, and 10% increase scenarios.

Additional Mass Sequestered Under Increase Scenarios: Aurora 7

Pollutant (metric weight)	Current Mass	2% Increase	4% Increase	10% Increase
CO (kg)	36.21	0.72	1.45	3.62
NO2 (kg)	425.95	8.52	17.04	42.60
O3 (T)	1.91	0.04	0.08	0.19
PM2.5 (kg)	62.35	1.25	2.49	6.24
SO2 (kg)	96.13	1.92	3.85	9.61
PM10 (kg)	635.84	12.72	25.43	63.58
CO2seq (T)	233.64	4.67	9.35	23.36
CO2stor (T)	9119.95	182.40	364.80	912.00

Table 6.1.9: Illustrates additional mass of sequestered, removed, or stored pollutants when tree cover increases by 2%, 4%, and 10% in Aurora 7 Neighborhood study area.

Additional Economic Value Under Increase Scenarios: Aurora 7

Pollutants	Current Values (USD)	2% increase	4% increase	10% increase
CO	$53.04	$1.06	$2.12	$5.30
NO2	$308.53	$6.17	$12.34	$30.85
O3	$5,681.14	$113.62	$227.25	$568.11
PM2.5	$1,947.92	$38.96	$77.92	$194.79
SO2	$22.14	$0.44	$0.89	$2.21
PM10	$4,377.99	$87.56	$175.12	$437.80
CO2seq	$9,079.50	$181.59	$363.18	$907.95
CO2stor	$354,423.02	$7,088.46	$14,176.92	$35,442.30

Table 6.1.10: This table shows current values of pollutant removal (in 2018 USD) and estimates for additional value if the Aurora 7 Neighborhood study area were to increase its canopy coverage by 2%, 4%, and 10%.

Martin Acres Neighborhood

As presented in subsection 4.5, the Martin Acres neighborhood study area had both the highest canopy cover (33.9%) of the six study areas and the highest impermeable surface cover

(41.2%) of the three neighborhoods. The 2%, 4%, and 10% increase scenarios would bring Aurora 7's canopy cover up to 35.9.9%, 37.9%, and 43.9%, respectively, and the neighborhood's impermeable surface cover down to 39.2%, 37.2 %, and 31.2%, respectively. The following tables report additional mass and economic value that would be gained under 2%, 4%, and 10% increase scenarios.

Additional Mass Sequestered Under Increase Scenarios: Martin Acres

Pollutant (metric weight)	Current Values	2% Increase	4% Increase	10% Increase
CO (kg)	55.91	1.12	2.24	5.59
NO2 (kg)	657.60	13.15	26.30	65.76
O3 (T)	2.95	0.06	0.12	0.30
PM2.5 (kg)	96.26	1.93	3.85	9.63
SO2 (kg)	148.42	2.97	5.94	14.84
PM10 (T)	1.08	0.02	0.04	0.11
CO2seq (T)	360.70	7.21	14.43	36.07
CO2stor (T)	14079.85	281.60	563.19	1407.99

Table 6.1.11: Illustrates additional mass of sequestered, removed, or stored pollutants when tree cover increases by 2%, 4%, and 10% in Martin Acres Neighborhood study area.

Additional Economic Value Under Increase Scenarios: Martin Acres

Pollutants	Current Values (USD)	2% increase	4% increase	10% Increase
CO	$81.88	$1.64	$3.28	$8.19
NO2	$476.32	$9.53	$19.05	$47.63
O3	$8,770.83	$175.42	$350.83	$877.08
PM2.5	$3,007.30	$60.15	$120.29	$300.73
SO2	$34.18	$0.68	$1.37	$3.42
PM10	$6,758.97	$135.18	$270.36	$675.90
CO2seq	$14,017.39	$280.35	$560.70	$1,401.74
CO2stor	$547,176.48	$10,943.53	$21,887.06	$54,717.65

Table 6.1.12: This table shows current values of pollutant removal (in 2018 USD) and estimates for additional value if the Martin Acres Neighborhood study area were to increase its canopy coverage by 2%, 4%, and 10%.

Comparing Canopy Cover Increases Via Tree Cover to Impermeable Surface Cover Proportions (Data Report)

The following subsection will report shifts in tree cover to impermeable surface cover proportions under canopy increase scenarios (increasing by 2%, 4%, and 10%). Changes in proportions are based off of the previously discussed 2018 i-Tree Canopy reports across the six study areas (see chapter 4). Please note that *changes in proportions assume that additional tree cover reduces impermeable surface cover by the same amount.*

Current Tree Cover to Impermeable Surface Cover Proportions

Study Area	Tree Cover	Impermeable Surface Cover	Tree to IS proportion
29th Street Mall	6.01%	84.00%	**0.07**
Pearl Street Mall	13.60%	83.70%	**0.16**
CU Boulder Main Campus	20.20%	54.10%	**0.37**
Harlow Platts	28.50%	38.50%	**0.74**
Aurora 7	33.20%	38.10%	**0.87**
Martin Acres	33.90%	41.20%	**0.82**

Table 6.2.1: The current proportions of tree cover to impermeable surface cover for all six study areas.

Tree Cover to Impermeable Surface Cover Proportions Under the 2% Increase Scenario

Study Area	Tree Cover	Impermeable Surface Cover	Tree to IS proportion
29th Street Mall	8.01%	82.00%	**0.10**
Pearl Street Mall	15.60%	81.70%	**0.19**
CU Boulder Main Campus	22.20%	52.10%	**0.43**
Harlow Platts	30.50%	36.50%	**0.84**
Aurora 7	35.20%	36.10%	**0.98**
Martin Acres	35.90%	39.20%	**0.92**

Table 6.2.2: Proportions of tree cover to impermeable surface cover across the six study areas if there was a 2% increase in tree cover and a 2% decrease in impermeable surface cover.

Tree Cover to Impermeable Surface Cover Proportions Under the 4% Increase Scenario

Study Area	Tree Cover	Impermeable Surface Cover	Tree to IS proportion
29th Street Mall	10.01%	80.00%	**0.13**
Pearl Street Mall	17.60%	79.70%	**0.22**
CU Boulder Main Campus	24.20%	50.10%	**0.48**
Harlow Platts	32.50%	34.50%	**0.94**
Aurora 7	37.20%	34.10%	**1.09**
Martin Acres	37.90%	37.20%	**1.02**

Table 6.2.3: Proportions of tree cover to impermeable surface cover across the six study areas if there was a 4% increase in tree cover and a 4% decrease in impermeable surface cover.

Tree Cover to Impermeable Surface Cover Proportions Under the 10% Increase Scenario

Study Area	Tree Cover	Impermeable Surface Cover	Tree to IS proportion
29th Street Mall	16.01%	74.00%	**0.21**
Pearl Street Mall	23.60%	73.70%	**0.32**
CU Boulder Main Campus	30.20%	44.10%	**0.68**
Harlow Platts	38.50%	28.50%	**1.35**
Aurora 7	43.20%	28.10%	**1.54**
Martin Acres	43.90%	31.20%	**1.41**

Table 6.2.4: Proportions of tree cover to impermeable surface cover across the six study areas if there was a 10% increase in canopy cover and a 10% decrease in impermeable surface cover.

Comparing Tree Cover to Impermeable Surface Cover Proportions Across All Scenarios

Study Area	Current Proportion	2% Increase	4% Increase	10% Increase
29th Street Mall	**0.07**	**0.10**	**0.13**	**0.21**
Pearl Street Mall	**0.16**	**0.19**	**0.22**	**0.32**
CU Boulder Main Campus	**0.37**	**0.43**	**0.48**	**0.68**
Harlow Platts	**0.74**	**0.84**	**0.94**	**1.35**
Aurora 7	**0.87**	**0.98**	**1.09**	**1.54**
Martin Acres	**0.82**	**0.92**	**1.02**	**1.41**

Table 6.2.5: A side by side comparison of proportional tree cover to impermeable surface cover changes across the six study areas with 2%, 4%, and 10% tree cover increase and impermeable surface decrease, respectively.

A Discussion of Increase Scenarios: Are They Achievable?

While section 6.1 reported on increases in mass and economic value as a direct function of current i-Tree Canopy estimates, section 6.2 focused more on the shift in canopy and impermeable surface cover. It is important to understand the advantage of increasing our urban canopy, but it is hard to grasp without information on the physical and economic value of doing so (section 6.1) alongside an understanding of land cover shifts (section 6.2). The first set of information can be used for hard data cost benefit analysis while the other can be used for the much more difficult task of determining heat island index mitigation under increase scenarios. The heat island effect is a factor of impermeable surfaces exposed to solar radiation, which then warms the surrounding air. When areas have low amounts of exposed impermeable surfaces relative to other cover types the impacts of the heat island effect can be minimized. The proportions of tree cover to impermeable surface cover can be used as a tool to understand this with proportions closer to or exceeding 1 having a higher chance of minimizing heat impacts.

Since i-Tree Canopy computes mass and economic value as a function of tree cover over area it was simple to formulate tables that demonstrate 2%, 4%, and 10% increase scenario impacts. In essence, a 2%, 4%, or 10% increase in canopy cover results in an equivalent 2%, 4%, or 10% increase in both mass and economic value. This simple equivalency of canopy increase and impact allows any i-Tree Canopy dataset to be extrapolated on, forming projections on various increase or decrease scenarios.

While a 10% canopy increase yields the most dramatic results across all study areas, it is not a feasible goal for most of them, refuting the hypothesis that all canopy areas could benefit from large increases to canopy cover. A 10% canopy increase could potentially be feasible in areas that currently have lower than Boulder average coverage (such as 29th Street Mall and Pearl

Street Mall), or on The University of Colorado Boulder main campus where open fields present planting potential. However, infrastructure (such as buildings and pavement), as well as recreational considerations (such as outdoor concert/rally venues and practice fields), create barriers to implementation. Similar infrastructure barriers can be seen in neighborhood settings (Aurora 7, Harlow Platts/Table Mesa, and Martin Acres) from housing and public roads, but have additional complications from existing canopies.

A more realistic goal would be to increase canopy cover by 2% in the study areas. This is especially true of the neighborhood study areas which are unlikely to be able to implement a 10% increase, or perhaps even a 4% increase in canopy cover. It is also worth noting that because the three neighborhoods start with the highest tree to impermeable surface proportions, smaller changes in cover between the two types have a higher impact- supporting hypothesis 3 as stated in chapter 1. This phenomenon works in the same way that giving all citizens the same flat-rate tax break would, with upper-income citizens receiving a substantially larger amount of money than lower-income citizens.

Referring to table 6.2.5, the neighborhood study areas all show a positive proportional change of 0.10 or greater for every 2% shift of canopy increase and impermeable surface decrease. By comparison, Pearl Street Mall and 29th Street Mall both increase by 0.03 for every 2% shift. Following this 2% shift pattern, the two malls would have to shift cover types by a little over 6% to reach the same proportional change that neighborhood study areas do with a 2% shift. Along the same lines, The University of Colorado, Boulder main campus study area could improve its cover proportions by 0.10 by increasing its canopy cover by 4% (as demonstrated in table 6.1.2). Thus, potential long-term goals for the urban areas and CU's main campus could be 6% and 4%, respectively.

As mentioned earlier, existing tree arrangements in all study areas pose barriers to canopy increase because current layouts may not utilize the most efficient placement of trees. For example; there's an area that, if unplanted, could host five trees but currently houses three, with existing trees planted equidistant from each other. This current arrangement makes it difficult to plant new trees because the spaces allotted between existing trees cannot support another. Consequently, it may make more sense to simply decrease impermeable surface cover by increasing grass cover. Green roof initiatives and planting grasses between street trees (which tend to be surrounded by pavement) offer manageable ways to shift away from high amounts of impermeable surface coverage in more urban environments. Encouraging homeowners to introduce native, low water maintenance grasses between trees in their yards and keeping established trees (which provide wider canopies than younger trees) healthy in order to shade their roofs will help reduce the impact of existing impermeable surfaces.

CHAPTER 7: FINAL CONCLUSIONS, RECOMMENDATIONS, LIMITATIONS AND FURTHER RESEARCH

FINAL CONCLUSIONS

When I began this project eight months ago, I asked, "How does canopy cover vary across different types of land use in the City of Boulder?" In order to answer this question, I have: 1) compared the average City of Boulder canopy cover, 15.9%, to six study areas of differing land use (chapter 4), 2) conducted on the ground surveys to determine if ash tree density reflects city estimates of 12% on private land (chapter 5), and 3) looked into the rewards of and potential for increasing canopy cover by 2%, 4%, and 10% (chapter 6). Here I discuss my original research question by determining whether my four hypotheses were supported or refuted.

My first hypothesis, that urban land use areas (such as outdoor malls) will have significantly lower canopy cover and dramatically higher impermeable surface area than other land use types, was supported by the data presented in chapter 4. The most notable example of this was the clear difference between 29th Street Mall (an urban study area) and Martin Acres (a neighborhood study area). 29th Street Mall features the lowest canopy cover rate of all the study areas, a mere 6.01%, and the highest impermeable surface cover of all the study areas at 84%. In contrast, Martin Acres boasts 33.9% canopy cover and the third lowest impermeable surface cover, 41.2%. This means that Martin Acres has a canopy that is nearly six times the size of 29th Street Mall's, and an impermeable surface cover of less than half that of 29th Street Mall's. In terms of tree cover to impermeable surface cover proportions, 29th Street Mall's proportion was .07 compared to Martin Acres whopping 0.82. Thus, my first hypothesis was firmly supported.

My second hypothesis, that nearby neighborhoods will have statistically similar tree cover and ash tree densities, was supported by the four T-tests conducted in chapter 5. All four T-tests had p-values of greater than 0.05, meaning they failed to refute the null hypothesis that the two areas were similar in terms of tree density, ash tree density, and properties with signs of EAB infestation. In this chapter, I also found that the two neighborhood study areas featured less than the city estimated 12% ash tree cover. However, this may not be true of all City of Boulder neighborhoods because the two I studied were a geographically short distance from each other (around 3.5 miles apart) and had both been targeted with EAB education campaigns.

My third hypothesis, that study areas that currently have high canopy cover would receive disproportionately high benefits from small increases in canopy cover compared to study areas with low canopy cover, was supported by findings in chapter 6. Shifts in tree cover to impermeable surface cover proportions across 2%, 4%, and 10% increase scenarios illustrate that areas with high canopy cover gain the most benefit from minimal increases in canopy cover, much like how a flat-rate tax break disproportionally benefits those who are already wealthy. For instance, I found that a 2% increase in canopy cover in the neighborhood study areas resulted in the same proportional shift (0.10) that a 6% canopy increase would allot the urban study areas (29th Street Mall and Pearl Street Mall).

My fourth hypothesis, that the six study areas could all benefit from large increases to canopy cover, was supported but found to be unachievable in chapter 6. The growth in mass sequestered and economic value of the canopy as seen in tables 6.1.1 through 6.1.12 exhibit how all of the study areas could indeed benefit from any amount of canopy increase. However, barriers to implementation arise in the current layout of canopies, considerations for recreational spaces, and limitations due to existing infrastructure (building layout and existing pavement, for example).

The average canopy cover in the City of Boulder has been estimated to be 15.9% as of 2018 (City of Boulder Urban Forest Strategic Plan, 2018). However, I have found that this average is not seen across the three differing land use types I have examined in this thesis. Instead I found that highly urbanized areas (29^{th} Street Mall and Pearl Street Mall) are characterized by less-than-Boulder-average canopy covers (6.01% and 13.6%, respectively), the University of Colorado, Boulder main campus featured a higher-than-Boulder-average canopy cover of 20.2%, and the neighborhood study areas (Harlow Platts, Aurora 7, and Martin Acres) were set apart with far higher-than-Boulder-average canopy covers of at least 28% (28.5%, 33.2%, and 33.9%, respectively).

Recommendations:

Based on the conclusion that, while all study areas could theoretically benefit from canopy increases, such expansion is unachievable, I will make the following recommendations: First, the city should explore methods of reducing impermeable surface cover and its impacts wherever possible. One method of doing so would be to implement green roof initiatives and reward citizens for participating. For example, the city could encourage property owners to build sod-roof houses by offering property tax breaks to those who have sod roofing. Additionally, the city could minimize damages from storm-water runoff (caused by high impermeable surface area) by subsidizing water collection barrels for its citizens.

Second, as the city's urban forest shifts away from ash trees, these trees need to be replaced by fast-growing, low water-intensity species. These fast-growing trees will quickly replace the shade lost from ash tree removal. It is important to not only select low waterintensive species, but to include a large variety of species, especially those that can survive increasing weather extremes. In essence, in order to ensure the longevity of Boulder's urban canopy it is imperative to increase the biodiversity of the trees that exist within it.

With that being said, my third and final recommendation is that the city maintain its current canopy. The simplest way to increase shading over impermeable surfaces such as buildings and pavement is to help existing trees reach full growth. This means introducing educational programs that teach the public when to treat versus when to tear down, how to properly care for recently planted saplings, and the benefits of shade trees around the home. PLAY Boulder, the non-profit arm of Boulder's Parks and Recreation department, is currently piloting such a program. PLAY Boulder's new Tree Tenders program will educate citizens on subjects such as tree biology, tree planting, pruning and maintenance, and signs of emerald ash borer infestation. The new program is set to launch April of 2019.

LIMITATIONS AND FURTHER RESEARCH

The major limitation to my thesis was time. From start to finish, I had only eight months to decide on and focus my topic, determine my methods, carry out my investigations, and author my findings. Time was especially limiting when it came to my ground surveys. Ideally, I would have conducted these surveys across all six of my study areas, but there was simply not enough time to do so. Additionally, my ground surveys were limited in that they were not stratified across income levels (low-income to high-income neighborhoods) nor were they stratified across geographically different areas of Boulder. Further research is required to ascertain differences in tree density, ash tree density, and signs of EAB infestation across income levels and geographic space.

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APPENDICES

APPENDIX 1: ASH TREE IDENTIFICATION

The following ash tree identification guide was supplied to volunteers by Thomas Read from the City of Boulder Forestry Department.

ASH TREE IDENTIFICATION GUIDE

The Common Characteristics of Ash Trees

Ash trees are deciduous with an upright, oval to rounded silhouette and a dense canopy. Foliage is dark green above and paler below.

Ash Bud and Branch Arrangement:

Branches and buds of ash trees are located directly across from each other. They are **OPPOSITE**.

YES!

Ash trees **DO NOT** display staggered or **ALTERNATE** branching pattern.

NO!

Note:
Buds and limbs of ash trees often die and fall off, so not every single branch or bud will have an bud will have an opposite mate. Look at several examples to determine the branch arrangement.

Ash Leaves:

Ash have **COMPOUND** leaves which help make them easy to identify. Each leaf is made up of 5-11 leaflets. The leaflets are positioned opposite of each other, except for the solitary leaflet at the tip.

Leaflet margins may be smooth, serrated or toothed.

The leaflets vary in size depending on the species.

Ash Bark:

Ash bark is usually light to dark gray with a medium to course ridged or furrowed appearance; as the ash tree ages, the bark looks diamond shaped. On younger trees, the bark is smooth.

Ash Seeds:

The single winged seeds of ash trees are called **samaras**. Samaras hang in clusters.

For identification photographs and more information on ash trees and the threat that Emerald Ash Borer represents to their health please visit:
www.entm.purdue.edu/EAB

ASH TREE "LOOK-A-LIKES"

Trees that Resemble Ash

For identification photographs and more information on ash trees and the threat of Emerald Ash Borer please visit: www.entm.purdue.edu/EAB

BOXELDER

- Opposite branching habit
- Compound leaves 3 - 5 leaflets (instead of 5 - 11)
- Samaras are always in pairs instead of single like the ash

MOUNTAIN ASH

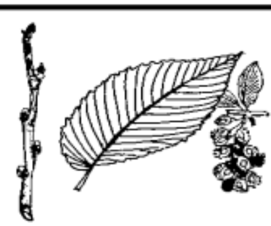
- Alternate branching habit
- Compound leaves
- Clusters of creamy white flowers
- Fruits are red-orange berries

SHAGBARK HICKORY

- Alternate branching habit
- Compound with 5 – 7 leaflets
- Hard-shelled nuts in a green husk

BLACK WALNUT

- Alternate branching habit
- Compound leaves with 9 - 15 leaflets
- Fruit is a large dark brown nut inside a green husk



ELM

- Alternate branching
- Leaves are simple with unequal leaf base

Appendix 2: Emerald Ash Borer Infestation Identification

The following emerald ash borer infestation identification guide was supplied to volunteers by Thomas Read from the City of Boulder Forestry Department.

Signs and Symptoms of EAB Infestation

Signs of EAB infestation include:

- Sparse leaves or branches in the upper part of the tree
- D-shaped exit holes approximately 1/8-inch wide
- New sprouts on the lower trunk or lower branches
- Vertical splits in the bark
- Winding, S-shaped tunnels under the bark
- Increased woodpecker activity

Many ash trees in Colorado are in poor health, which can make it even more difficult to determine if they are impacted by EAB. If you're not sure if a tree has EAB or not, the CSFS offers a diagnostics video at www.csfs.colostate.edu/emerald-ash-borer.

If an ash tree is experiencing dieback or appears unhealthy, have it examined by a professional. Landowners that suspect the presence of EAB in their ash trees should contact the Colorado Department of Agriculture (CDA) at (888) 248-5535 or send an email to CAPS.program@state.co.us.

Figure 16. *EAB is responsible for the death or decline of tens of millions of ash trees in at least 25 states. Photo: Dan West, CSFS*

Figure 17. *New sprouts grow on the lower trunk of an ash tree infested with EAB. Photo: James W. Smith, USDA APHIS PPQ**

Figure 18. *Woodpeckers are an important predator of EAB. Photo: David Cappaert, Michigan State University**

Figure 19. *D-shaped exit holes can indiciate the presence of EAB. Photo: Pennsylvania Department of Conservation and Natural Resources**

Figure 20. *Ash trees may be infested with EAB for up to four years before signs of decline are visible. Photo: David Cappaert, Michigan State University**

Figure 21. *Vertical splits in the bark are another sign that EAB has infested the tree. Photo: Joseph O'Brien, International Society of Arboriculture**

Figure 22. *S-shaped tunnels or galleries can be found under the bark of an infested ash tree. Photo: Ryan Lockwood, CSFS*

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