AN ASSESSMENT OF THE ECOSYSTEM SERVICES PROVIDED BY THE STREET TREES OF OLYMPIA WASHINGTON

by

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ABSTRACT

An assessment of the ecosystem services provided by the street trees within the City of Olympia, Washington.

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Urban forests provide a number of ecosystem services, including improved air quality, stormwater processing, cooling, and health benefits to the community and are considered by the literature to be an important component of city planning to become more sustainable and resilient. To date, the City of Olympia has not yet assessed the ecosystem services of their street trees, specifically how much these trees contribute to the health of the community and the environment in a given year. This study resolves this gap in research by answering the question: What are the annual ecosystem services provided by the street trees in Olympia, Washington? This study quantified the air quality, stormwater, energy savings, and carbon storage and sequestration services provided every year by street trees in both quantitative and monetary amounts. The study utilizes GIS tree inventory data from the City of Olympia's Urban Forestry Department on the conditions and dimensions of the 2,483 street trees. My results quantified the annual fiscal benefits and ecosystem services of the city's street trees using iTree Streets and iTree Eco software and include an ArcGIS geospatial analysis of the street trees population. The results of this thesis provide a more comprehensive assessment, including a cost-benefit analysis, of street trees for the City of Olympia. This study found that the annual ecosystem service benefits provided by the street trees outweighed the annual urban forest program costs, and determined that the energy reduction services of street trees were the most important service they provide to the City of Olympia and its residents.

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KEYWORDS

Anthropocene: a proposed geological epoch dating from the commencement of significant human impact on Earth's geology and ecosystems, including, but not limited to, anthropogenic climate change.

Ecosystem services: the broad range of beneficial services to humans as provided by natural systems.

GIS: geographical information systems mapping software used for geospatial analysis of landscapes.

Green infrastructure: refers to biotic systems—such as street trees, parks, and living shorelines—that replace or support the services provided by grey infrastructure.

Grey infrastructure: Man-made infrastructure, often within an urban environment, engineered to manage natural processes such as water flow, stormwater, and erosion.

iTree Eco (Eco): a software program designed to quantify forest structure, environmental effects, and value to communities.

iTree Streets (iTree Streets): a software program designed to analyze urban street trees by determining the ecosystem services and the cost-benefits of urban forestry planning and maintenance.

LID: low impact development is a form of green infrastructure related to site development and on-site stormwater processing using natural filtration processes.

NDVI: Normalized Difference Vegetation Index: a method to determine vegetation health using aerial imagery within GIS.

Street tree: a tree planted in the public right-of-way, usually in the planting strip between sidewalk and road, or approximately 10 feet from the curb or roadside if a sidewalk is not present.

Urban Forest: trees within an urban landscape growing on both public and private lands.

UHI: urban heat island effect. A measured increase in average temperature in urban areas dominated by non-porous surfaces and industrial processes.

Urban Resilience: the measurable ability of an urban system or community to withstand and quickly recover from stressors and shock.

Urban Sustainability: the theoretical perspective that natural resources and waste production within urban areas should be efficiently managed in order to support and enable the well-being of current and future populations of humans and other living things.

USFS: United States Forest Service.

Water interception: rainfall stored temporarily on tree leaves which then drips down the body of the tree, falls off the leaves into the ground, or is evaporated into the atmosphere.

Acknowledgments

This thesis was not created in a vacuum. The idea for this work came about while enjoying a beer with a friend and looking out over Downtown Olympia. I told him “I wonder what our trees are doing for us right now— how much stormwater are they processing? How much carbon are they storing?” My excitement about the thought, and the conversation that followed, led me down the rabbit hole of this research, which is now laid out in detail on the following pages. Along the way many people held space for me as I thought aloud; guiding me as I structured my research design, and listened to me lament about the challenges I faced as I progressed further towards the finish line. I am thankful to you all.

The skills to create my research design and GIS maps were gained over the two years of the Master of Environmental Studies program at Evergreen State College, and I want to thank Kevin Francis and the entire faculty for accepting me into this program.

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Thank you to Julian Wischniewski and Anna Duron, for being an amazing peer-review team, and to Susan McCleary for taking me on as an intern and for cheering me on as I worked to complete my research while working with the City of Olympia. To Michelle Bentley for having tea with me and encouraging me along while patiently answering my million-and-one questions, and to the Woody Schaufler for providing me with the vital information needed to make this research possible.

Last, but never least, I dedicate this thesis to the one person without whom graduate school would have been out of reach: my best friend, adopted family-member, and favorite human-robot-alien hybrid, Michael Zarghami.

Thank you.

INTRODUCTION

Like many other cities today, the City of Olympia is dealing with climate-related stressors and faced with the difficult task of creating and implementing climate adaptation plans for the health and sustainability of the urban environment and their residents (Haub, Harrington, McGowan, & Reed, 2007). The natural benefits of urban trees can help to mitigate the stressors of climate change within the City of Olympia, though it is still underrepresented in regional climate mitigation plans (Meerow, Newell, & Stults, 2016; Pearlmutter et al., 2017; TRPC, 2017). At the same time, the approaches to urban forestry and tree valuation in Olympia have focused on aesthetic amenities and the traditional metrics of tree appraisal and tree maintenance costs— what has not yet been researched are the many benefits of their trees for the social, economic, and environmental health of the city and its residents, referred to as ecosystem services (AMEC, 2011; CFC, 2016; Roush & McFarland, 2006). Ecosystem services are the broad range of services provided by trees including the ability of urban trees to improve air quality, process stormwater, store and sequester carbon, and reduce energy demands by cooling the surrounding environment (Grant, 2012; Young, 2011).

This study highlights the importance of the many services provided by trees to the health and well-being of city residents, and to the long term sustainability of the City of Olympia in the face of the complex challenges of regional climate change and climate adaptation. Determining the exact content and distribution of the benefits, and their extent, is the key to understanding the important contributions of our urban trees. By utilizing the existing street tree inventory maintained by the City of Olympia's urban forestry program, regional satellite imagery in Geographical Information System (GIS) software, and iTree Streets and iTree Eco (ECO) urban forestry software, this study has determined the costs and benefits of street tree ecosystem services. In addition, this study was able to determine the annual contribution of street trees to improve air quality, reduce stormwater flows and energy demands, and sequester and store carbon in both weight and dollar amount. The exciting results of this study further illustrate the importance of including street trees in urban planning for climate change adaptation within the City of Olympia and Thurston County, and the need for more research on the contributions of our entire urban forest.

Lay of the Land

The 2,500 street tree plots maintained by Olympia's Urban Forestry department collectively make up only *part* of the urban forest. **Urban forests** consist of trees on both public and private lands, which together create a green network that offers the community the array of services referred to as **ecosystem services** (Young, 2011). The broad range of services includes the ability of urban trees to regulate air temperatures, shade sidewalks and nearby buildings, store and filter stormwater, and store and sequesters carbon (Grant, 2012). The ecosystem services of urban forests are considered by many cities throughout the United States to be an important component of urban planning in efforts to become more sustainable and resilient (Hastie, 2003; Kuehler, Hathaway, & Tirpak, 2017; Young, 2011).

In this study, I use a sample of street trees to represent the urban forest within the City of Olympia to determine these beneficial services. This sample is composed mainly of a deciduous species, with an average trunk size measured at diameter breast height (DBH) of less than 9 inches. Taking these factors into account, the methodology outlined in this study illustrates how we can begin to use existing street tree inventory data to quantify, monetize, and thus understand in a number of different ways their beneficial ecosystem contributions.

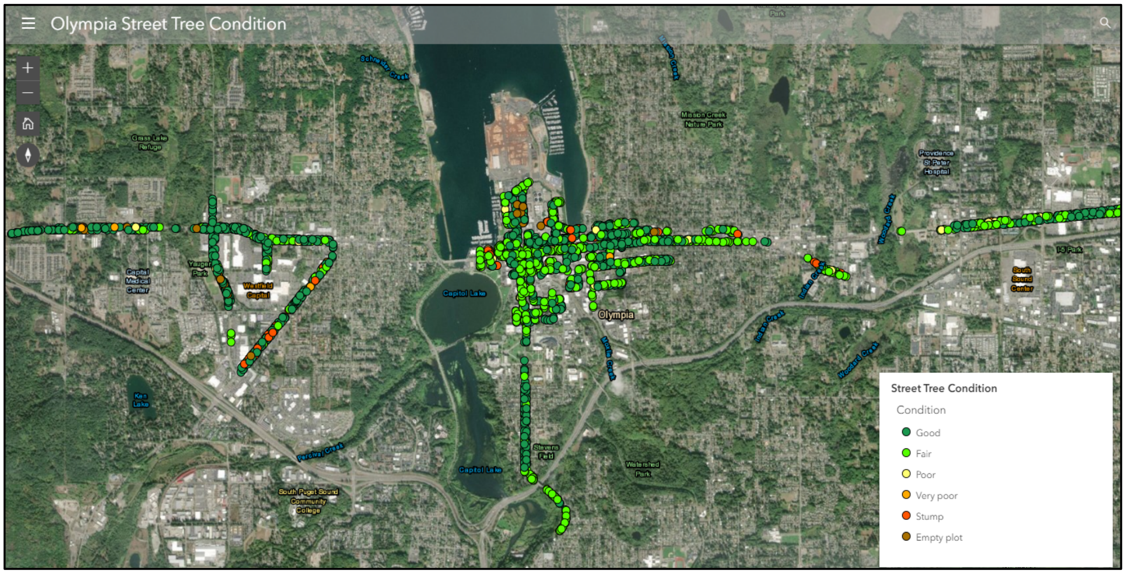


Figure 1. Tree plot locations and the tree conditions map. These plots are maintained by the City of Olympia.

The street tree inventory of Olympia as seen in Figure 1 is fairly new, having been created in GIS with funds from a Department of Natural Resources (DNR) grant in 2016 (CFC, 2016). The inventory grant funds allowed for a maximum of 2,500 trees to be assessed by a trained arborist and entered into the inventory database, so the main arteries throughout the City and downtown Olympia were chosen for inclusion in the GIS inventory for seasonal tree maintenance. These areas were prioritized primarily because the City recognized that downed limbs in these areas, especially during extreme weather events and natural disasters, would block the roads, bus routes, and emergency vehicles from being able to move throughout the city to provide essential services (W. Schaufler, pers. comm. Mar. 5, 2020). City workers needed information about the trees to maintain them properly. Additionally, since part of the Downtown Strategy for Olympia includes street trees as an integral part of their plan for beautification and community enhancement, tree care was prioritized for that area, which in 2016 included approximately 660 street trees (CFC, 2016; Roush & McFarland, 2006).

Regional tree studies and study significance

Traditional methods of valuation rely on calculations which determines the dollar value of a tree based on the potential costs of treatment, replacement, and property value increase (Roush & McFarland, 2006). In 2016, the Department of Natural Resources estimated the entire urban forest of Olympia to be worth approximately $6,100,000 (CFC, 2016). Although impressive, this value did not include the annual fiscal and environmental benefits provided by the street trees. This research adds the value of those benefits provided by street trees by using iTree software and visualizes them using

ArcGIS mapping software (AMEC Earth & Environmental Inc., 2011; Roush & McFarland, 2006).

To determine the value of Olympia street trees, this study utilizes urban forestry software that has embedded peer-reviewed scientific models that calculate the annual contributions that urban trees provide. iTree Streets and iTree Eco are publically available urban forestry software created in partnership with the USDA Forest Service and the Arbor Day Foundation, to support the efforts of urban forestry programs to secure funding and support urban tree conservation. These peer-reviewed tools quantify the ecosystem services in quantitative and monetary terms provided by trees in a given region based on collected tree health and dimensions (Vargas, 2018). iTree software has been used in many peer-reviewed studies and urban forestry assessments, and considered by many arborists, and this author, to be reliable for estimating the services trees provide in urban environments such as the City of Olympia (American Forests, 2008; Asselmeier, et al., 2019; Grant, 2012). A further discussion of iTree Streets and iTree Eco can be found in the Methodology and Results Chapter of this thesis.

Thurston County has conducted an urban tree canopy (UTC) assessment to support sustainable planning for future urban growth, but the scope of their investigation did not include the developed urban areas of Olympia. The UTC assessment focused solely on the unincorporated urban growth areas of Thurston County— areas just beyond the current city boundaries projected to be urbanized and developed within the next 20-years (AMEC Earth & Environmental Inc., 2011). My study will be focusing on the urban core and main thoroughfares of Olympia to fulfill this gap in research.

To date, the Master Street Tree Plan (2001-2011) provides the most comprehensive report on the urban forest of Olympia, but this report focused on the logistics of urban forestry planting, maintenance costs, and current policies for street trees, and does not include an assessment of the ecosystem services provided by trees (Roush & McFarland, 2006). Although trees are considered important for healthy water, air, and communities, the report does not include supporting data on the trees actual contribution to local air and water quality, or to public health in a given year (Roush & McFarland, 2006, pp. 4). Additionally, the Master Street Tree Plan is now dated and requires new research and an updated street tree assessment (M. Bentley, pers. comm. Jan. 16, 2020). This study could help to fill this gap with new research using the street tree inventory data provided by the City of Olympia's urban forestry department.

The City of Olympia is listed as a Tree City USA Community, and has met the Arbor Day Foundation program requirements for the past 26 years ("Tree City," 2019). Olympia may be proud of its urban trees; however, their ongoing urban forestry efforts could be supported and strengthened by new research on the street trees and the services they provide. To that end, my research responds to this question: What are the ecosystem services of the street trees in the City of Olympia, Washington? The research concentrated on annual air quality benefits, stormwater processing potential, carbon storage, sequestration, and carbon emission mitigation, and the reduction of building energy demands. Throughout this investigation I also investigated any potential disservices associated with these trees. The research and results from this study have also been tailored into education and outreach materials for general public audiences for the

City of Olympia’s urban forestry department to raise awareness of this topic, and to garner support for future urban forestry program costs.

Before reaching these conclusions however, we must first understand Olympia’s street trees and urban trees in the larger context of existing scientific literature, and how cities shape (and are shaped by) the natural world. By extension, we will also consider how traditional value systems dictate how we perceive and interact with urban trees in urban environments. In the next section we will take a closer look at the urban landscape and the role that trees play in this manufactured environment.

LITERATURE REVIEW

Urban environments as ecosystems

The world, we are told, was made especially for man
— a presumption not supported by all the facts.

— John Muir, A Thousand-Mile Walk to the Gulf

Some people would hardly consider the city in which they live an ecosystem. And yet, despite the dominance of concrete material and industrial processes, the urban environment behaves much like a natural ecosystem. It may differ qualitatively from a natural ecosystem, but the system dynamics of energy and material exchanges mirror those of the natural world (Samson Ch.1; Pearlmutter et al., 2017). The city has its own urban hydrologic cycle, weather patterns, and localized climate. It has its own familiar flora and fauna, and systems of transit that move energy and materials from one place to another. We cannot take cities out of the natural landscape in the same way that we cannot separate ourselves from the natural world in which we all live (Roszak, 1992). If we were to walk through a city, we could see all around us the ways we are rethinking and redesigning our natural and man-made surroundings. In this section we will discuss the city environment and the theories of urban sustainability as it relates to urban planning and forestry for the long-term health of the city, its residents, and its trees.

An increasing number of academics and practitioners approach the urban environment as an ecosystem; the theory has even prompted entirely new disciplines of study, such as **Urban Ecology** (Gaston, Davies, & Edmondson, 2013). The attention to the city as a complex system comes at a time when urbanization is happening at a pace and scale never before seen (O'Neill et al., 2010). With this trend comes the growing need to make our cities cleaner, more resilient, and sustainable (Fitzgerald, 2010; Grant, 2012; Young, 2011). As Theodore Roszak (1992) said about cities, "Nothing has absorbed more energy; nothing projects more of our aspirations" (pg. 215). The city is a socio-ecological conglomeration, and the human is a unique character that affects the biophysical behavior of the system by its participation (Meerow, Newell, & Stultz, 2016). We humans are an integral part of, and actively change our urban environments, simply by existing within them. Every decision we make to add or take away elements in our homes and on our properties collectively change our cities and how we see ourselves within that collective system.

Researchers, and now city professionals, are increasingly examining urban dynamics on large spatial scales and embracing complex systems theories, such as resilience theory, embedded ecological-based services, and the theory of sustainability (Turner, Gardner, O'Neill & O'Neill, 2001. Alberti et al., 2003). In turn, urban forestry dynamics, management, and design continue to evolve as new research is conducted on the ecology of the city and on the concept of green infrastructure within urban planning as a tactic for urban sustainability (Grant, 2012). **Urban sustainability** is generally considered to be urban planning and governance that support the health of socio-ecological systems and considers the well-being of current inhabitants without compromising future generations' ability to access the same resources (Baharash, 2017; Suzuki et al., 2010). Planning sustainable healthy urban ecosystems emphasizes three priorities: social, economic, and ecological, which are (ideally) considered in tandem (Seitzinger et al., 2012). When city planners come together to build climate mitigation plans, improve public transit systems, or work to plant trees in lower-income communities, we are seeing this theory of urban sustainability in action (Haub et al., 2007; Vogel et al., 2016).

The concept of green infrastructure as an essential component to the long-term health of the urban ecosystem is a growing trend across the disciplines of landscape architecture, urban planning, urban ecology, and urban forestry (Fitzgerald, 2010; Grant, 2012; Pearlmutter et al., 2017). As you may recall, green infrastructure, a type of sustainable infrastructure, refers to living systems—such as urban trees, and green spaces within the city—that replace or support the services provided by engineered infrastructure. **Grey infrastructure** uses engineered structures to control and manage natural processes, such as pipes and culverts to manage the urban hydrologic cycle. Where traditional grey infrastructure addresses a single function, green infrastructure typically provides ecological services that serve multiple functions. When used in tandem for stormwater management, these two approaches have the effect of reducing water runoff and pollution, and increasing water retention/aquifer replenishment (Gill, Handley, Ennos, & Pauleit, 2007). Urban green infrastructure, such as street trees, rain gardens, and non-porous surfaces, can be used to strengthen urban sustainability against climate-related challenges, but some argue that it is still underrepresented in the planning stages of urban design at large scales (Young, 2011). Unlike the built grey infrastructure of drainage systems and sea walls, the biotic system of green infrastructure is alive and is, to some extent, self-regulating and fragile, as are all living things (Grant, 2012).

These systems are all around us if we just take a look. In my backyard an apple tree grows. I don't tell it to grow leaves and bear fruit, and yet it does anyways. I can prune the limbs and leaves to encourage a certain shape, and tend to its soil to prolong its health into the cold months, but it is the tree that tirelessly takes in the sunlight and through photosynthesis produces the energy it needs to survive and produce fruit, exchange nutrients with the soil, and exhale the oxygen I breathe. In this way the network of living things within the urban environment work to clean the air, improve the soil, and shade their surroundings whether we ask them to or not—they do it as a consequence of their existence. Clean air, soil nutrient cycling, and shading are examples of the services provided by urban forests within the urban ecosystem, known collectively as ecosystem services. Green infrastructure provides these ecosystem services all around the urban environment, and if we pay close enough attention to look for them we can begin to see their importance.

Much like the tending of the apple tree to improve the health of the plant in order to benefit from the fruit it bears, a city needs to tend to its garden for the benefit and health of the system and its inhabitants. Some argue that a "broad view" of the many urban ecosystem dynamics is key to the undertaking of this stewardship of our green infrastructure of the modern city (Grant, 2012; Pearlmutter et al., 2017). There is a general consensus in the literature that a broad view or "systems thinking" approach to green infrastructure management (Krosinsky, 2016) has the potential to broaden the scope of how complex systems like urban ecosystems are planned, maintained, and experienced (Young, 2011). In line with this approach, the services provided by green infrastructure can be considered in four broad but interconnected ways: 1. cultural services, 2. regulating services, 3. provisioning services, and 4. habitat services (Pearlmutter et al., 2017 pg. 4).

Considering the many ecosystem services of trees as a form of sustainable infrastructure in this holistic manner can inform our urban forestry plans, goals, and actions within the City of Olympia. Understanding each of these ecosystem services; what they are, and how they interact, is the first link in this network approach to sustainable urban forestry planning. This examination will expand our understanding of how these natural services support the sustainability and resilience of our urban environments, and the importance of reexamining our traditional systems of tree valuation in light of these insights.

Trees as a green network

> *If the land mechanism as a whole is good, then every part is good, whether we understand it or not. If the biota, in the course of aeons, has built something we like but do not understand, then who but a fool would discard seemingly useless parts? To keep every cog and wheel is the first precaution of intelligent tinkering.*
>
> *—Aldo Leopold*

All systems depend on the continuous cycling of resources and why trees, rivers, and circulatory systems have branching growth structures. Everything lives by the exchanges of these resources; not inherently from the resources themselves (Glanzberg, 2020). Thinking of the urban forest like a branching circulatory system, it is this continuous flow and exchange of resources throughout the living network that makes the system valuable, sustainable, and resilient (Meerow, Newell, & Stults, 2016). This green matrix of vegetation that branches through the human-built environment supports the exchange of resources from the air, soil, and rain.

When considering the street tree network in Olympia, I argue here that the true value lies not in the appraised dollar value of an individual tree, but in their collective ability to improve the social, economic, and environmental health and resilience of the urban environment and its inhabitants by this process of exchange. Among many other benefits, urban trees play an important role in improving air quality, modulating city temperatures, and reducing stormwater flows, atmospheric carbon, and carbon emissions.

Trees have been studied extensively for their abilities to improve air quality in urban settings by intercepting pollutants such as ozone (O3) and fine particulate matter (Pearlmutter et al., 2017; Sicard et al., 2018). Tree canopies intercept gaseous air pollutants and polluting particulate matter (PM) when the air-born particulates fall back to earth in the form of either wet or dry deposition and collect on leaf and bark surfaces. The gaseous pollutants can also be absorbed through small openings in the surface of tree leaves called stomata (Pearlmutter et al., 2017, p. 22). Additionally, trees slow the movement of airflow, reducing the dispersal of pollutant particles in urban areas (Grote et al., 2016).

The ecosystem service of air quality improvement by urban trees has both social and economic benefits. For instance, air pollution exposure, including from fine particulate matter, nitrogen oxides, carbon monoxide, sulfur dioxide, and diesel exhaust, exacerbate asthmatic symptoms. Hospitals in Washington State charged about $73 million in 2010 for asthma-related hospitalizations, $43 million of which was charged to Medicaid and Medicare, and approximately $5 million of hospitalization bills was paid for by Washington State residents (Tran, Aldrich, & McDermot, 2013). Studies also show that asthma rates are higher for lower-income and minority populations, therefore the argument has been made that the widespread distribution of urban tree planting can help to improve the health and safety of these more vulnerable populations within our community (Tran et al., 2013; Young, 2011).

Conversely, trees can actually contribute to particulate ozone concentrations in cities through a process called **biogenic emissions** (Sicard et al., 2018). Many trees emit small biogenic volatile hydrocarbons (BVOCs), though the amount varies widely by species and microclimate conditions. The BVOCs may contribute to ozone levels in urban environments, but despite this, the benefits of trees for urban air quality outweigh the BVOCs emitted by some species (Gaston et al., 2013; Hastie, 2003; Mcpherson et al., 1997). BVOC emissions of Olympia's street trees have been included in this research in order to address this potential disservice by our street trees. Also included in this research are estimates for the important role of stormwater management by urban trees.

Green infrastructure as a tactic for stormwater management may be still fairly new as a management approach by city stormwater departments, but it is growing in interest and popularity (Berland et al., 2017). Grey infrastructure (such as pipes) has been the traditional approach for cities to control the movement of water through the urban landscape, but this system can malfunction or become overwhelmed during extreme precipitation events (Seattle, 2018). This is in large part due to the very nature of the urban landscape and what is referred to as the **urban hydrologic cycle**. Impervious surfaces effectively convey large volumes of stormwater and pollutants in urban areas dominated by pavement and cement. This lack of porous surface types typical in undisturbed landscapes also reduces the rates of infiltration through soil and vegetation to recharge aquifers and filter pollutants before reaching nearby water bodies (Berland et al., 2017; City of Olympia, 2016). A network of green infrastructure in an urban area can support traditional infrastructure in processing stormwater through infiltration through the soil and evapotranspiration from the leaves.

Thurston County and the City of Lacey recognized the ecosystem service of our urban trees as a viable and important tactic of reducing urban stormwater, erosion, and improving local water quality in their urban forest assessments (AMEC Earth &

Environmental Inc., 2011; Madden et al., 2013). Using our urban trees as a green stormwater support system in a region like Olympia, which experiences high annual precipitation rates, would seem to be a well-suited application for stormwater management.

Stormwater utilities staff working for the City of Olympia have their doubts about the effect of street trees diminishing the volume of stormwater because of the predominance of deciduous street trees (J. Roush, pers. comm. Feb. 10, 2020). Rainfall patterns in Western Washington create wet winters when deciduous trees drop their leaves, and dry summers when tree canopies are full (SWMP, 2019; “Weather Atlas,” n.d.). Some experts argue that inadequate research has been done on the ecosystem services of urban trees, and this research gap hinders the reliance on trees by stormwater utility managers as a viable approach to stormwater management (Kuehler, Hathaway, & Tirpak, 2017). Therefore, this study includes an assessment of stormwater services by street trees and quantifies the average amount of stormwater processed by Olympia’s street trees each year and it’s associated dollar value. Also included in this study are the important contributions by trees to mitigate carbon emissions and sequester carbon.

The contribution of trees to carbon storage and sequestration are widely recognized and studied as an important ecosystem service (Mcpherson et al.; Glaeser and Kahn, 2010; US DOE, 2008). Within the urban environment, this is an especially important ecosystem service since approximately 80% of the U.S. population lives in an urban area (as of 2020), and research suggests that as much as 80% of global emissions originate from cities (Hastie, 2003; O’Neill et al., 2010). Gaia Vince argues in *Adventures in the Anthropocene* that this could actually be seen as an opportunity for global carbon emissions to decline substantially if we shift our urban-industrial planning to sustainable urban planning (Vince, 2014, pg. 345). Trees help curb carbon emissions by reducing the temperature of the urban environment and nearby buildings in the summer, thereby reducing the energy demands for air-conditioning, and by reducing wind-chill in winter months, thereby reducing energy demands for heating. Some studies estimate cooling costs in summer months to be reduced by an average of 27%, and 7% reduction in heating costs in the winter (Hastie, 2003).

Trees also actively sequester atmospheric carbon as they grow, and store carbon in their above and belowground material over the life of the tree. In a Chicago tree study, the urban forest was calculated to sequester 155,000 tons of carbon each year, and researchers have estimated that the urban forests throughout the United States have collectively stored 700 million tons of carbon with an associated value of $14.3 billion (Chicago citation). I argue that part of sustainable urban planning is recognizing these services in urban forestry city programs and supporting the natural process of carbon storage and sequestration by keeping our trees healthy and in the ground for as long as possible.

With these many ecosystem services in mind and the guiding principles of urban sustainability as a conceptual framework, we can better reimagine our cities as we seek new ways to adapt to climate change. These changes in climate conditions are not only a call to action for humans to readjust our current models of behavior and design, but a force that will require a shift to more holistic management tactics for urban forestry.

Urban trees in a changing world

> *But when the storm is over, and we behold the same forests tranquil again…and consider what centuries of storms have fallen upon them since they were first planted… we cease to deplore the violence of her most destructive gales, or of any other storm-implement whatsoever.*
>
> *—John Muir, A Windstorm in the Forest*

Like many other regions in the world, the Pacific Northwest (PNW) has observed an increase in average temperatures over the past decade of 1.5 degrees F. and the IPCC models project that to increase by about 1.4 degrees F. by 2040 (USGCRP, 2018). The issues of climate change are dynamic and complex, so it seems appropriate to incorporate the dynamic and complex network of our urban forest and their ecosystem benefits in our regional climate mitigation plans. One of the Thurston Climate Mitigation Plan goals is to reduce carbon emissions by 45% by 2030 in an effort to help minimize global temperatures (TRPC, 2017). In this section I illustrate how, by using a more holistic perspective to mitigation planning, we can recognize how our urban forest can help to reach that goal of reducing energy demands, sequester and mitigate carbon emissions, and mitigate other climate-related stressors.

Often, the climate mitigation goals of cities rely on isolated projects aimed at single issues or criteria, such as air pollution or carbon emissions (Turner & Gardner, 2015). Although important, some argue that this scope is too narrow and will not be sufficient to meet the challenge of climate change facing many urban environments (Meerow, Newell, & Stults, 2016; Seitzinger et al., 2012). As argued above, the issues are interlinked and work on an array of diverse scales of time and space throughout the urban landscape, and must be responded to with an equally complex system of planning (Seitzinger et al., 2012). Sustainable city planning should incorporate conceptual perspectives that support current and future urban design (Joss, 2011). **Normative perspectives** encompass a variety of goals and values such as social, ecological, and economic goals and values that parallel the three pillars of sustainability. Seitzinger's three pillars, considered in combination with a normative perspective to governance, appear to be the most holistic approach to support urban adaptation simultaneously on multiple scales of development, maintenance, and governance. The normative perspective of urban forest planning in Olympia would support the recognition of trees in enhancing the social, economic, and environmental health of the city.

Scientific research supports the provision of urban trees to reduce air pollution and regulate air temperature at a time when air quality is becoming a point of concern for many counties, including Thurston County (TRPC, 2017). Increased summer temperatures mean an increase in energy demands for air-conditioning, and increased ozone levels in urban environments as a result of vehicle emissions being exposed to sunlight and heat (Sicard et al., 2018).

The increase in average annual temperatures is compounded by the **urban heat island** (UHI) effect which results from the dominance of non-porous land-cover, energy outputs of cooling systems and other urban industrial processes, and heat-holding nature of our man-made materials like steel and pavement, which can double the rate of urban temperature increase (Gaston, Davies, & Edmondson, 2013; Gregory et al., 2002). Studies have found that tree-lined streets, green-spaces, and rain swales all serve as multifunctional green infrastructure by cooling the surrounding temperatures and ameliorating the UHI effect, while also supporting the grey infrastructure stormwater system by reducing stormwater flows (Meerow, Newell, & Stults, 2017; USGCRP, 2018; Sicard, 2018).

Figure 2. Thermal infrared image indicating the daytime difference in radiative surface temperature between exposed and tree-shaded pavement. (Pearlmutter et al., 2017)

Locally, trees also help to cool the urban environment through canopy cover (Figure 2) and evapotranspiration (the collective evaporation from tree leaves and soil) and reduce the energy demand on surrounding structures, thereby mitigating carbon emissions from the air-conditioning units and local power plants, and improving urban air quality (Gaston et al., 2013; Young, 2011). A study done in 1994 in Chicago using iTree methodology showed that urban trees reduced energy use by between 5-10% and resulted in a city-wide savings $38 million each year (McPherson et al., 1994; McPherson et al., 1997). This reduction in energy demand has the effect of reducing carbon emissions from power plants and local A/C units within the city, therefore improving air quality (Mcpherson et al., 1997).

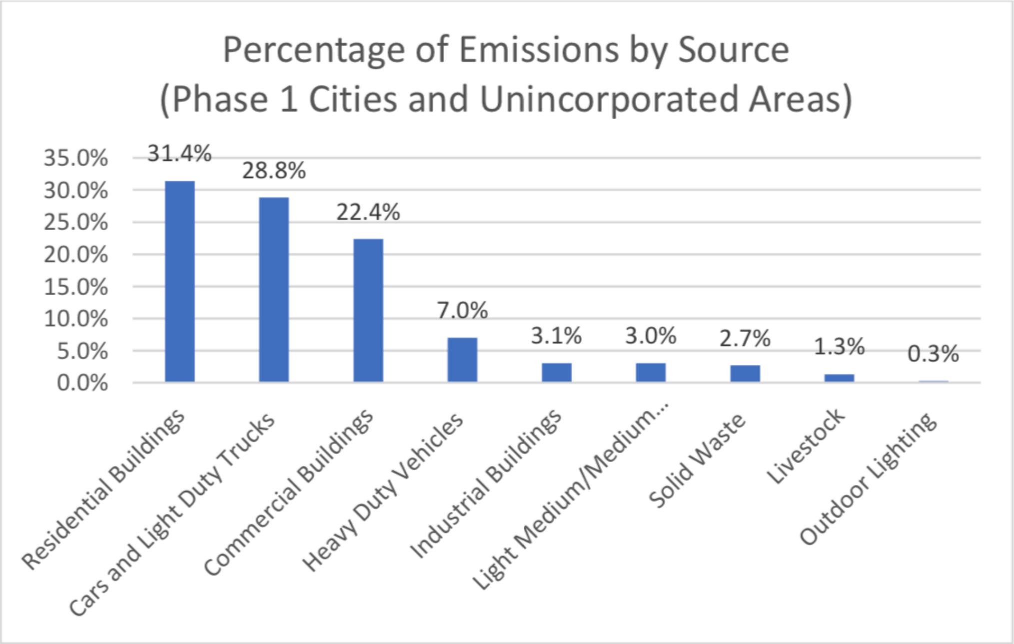
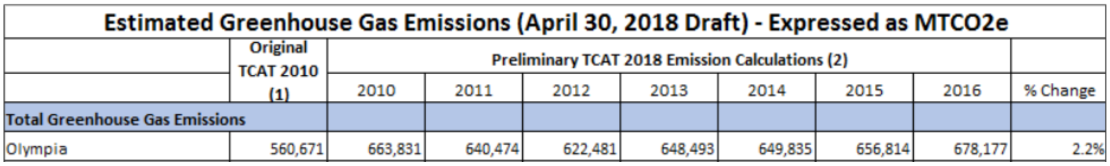


Figure 3. Thurston Climate Action Team report showing that the top emitters of greenhouse gases are building and vehicle emissions.

Typical city residents are exposed to an average of 200 different classes of air pollutants in a day (Sicard et al., 2018). According to the Thurston Climate Action Team, the second leading emission class source, behind electricity and gas, was cars and light-duty trucks and the heating and cooling of buildings as seen in Figure 3 (Olympia & Lacey, 2010). With growing urbanization trends and increasing summer temperatures at mid-latitudes of the Northern Hemisphere, standards for air quality are becoming a priority issue for local climate mitigation planning (TCAT; Sustainable Thurston, 2013). As of 2018, the Thurston Regional Planning Council status report shows rising annual emission rates over time, as seen in Table 1.

Table 1. status report for TRPC in spring 2018 shows upward trend in emissions by year.



Estimated Greenhouse Gas Emissions (April 30, 2018 Draft) - Expressed as MTCO2e

	Original TCAT 2010 (1)	Preliminary TCAT 2018 Emission Calculations (2)							
		2010	2011	2012	2013	2014	2015	2016	% Change
Total Greenhouse Gas Emissions									
Olympia	560,671	663,831	640,474	622,481	648,493	649,835	656,814	678,177	2.2%

One consequence of the increased temperatures and emissions is the potential for the increase of low-level ozone, created when sunlight reacts with the emission particles from vehicles and energy supply industries. Trees within our cities have canopy leaves that intercept these airborne pollutants including ozone, as well as harmful particulate matter smaller than 10 microns that enter the lungs of city residents and lead to increased asthma and exacerbate cardiovascular conditions (Grant, 2012; Tran et al., 2013).

Although the services of trees in the urban landscape could be recognized as a response to mitigate some of the challenges faced by cities due to climate change, humans and our urban environments are not the only things stressed by climate change—trees are stressed by the changes in their environment and urban foresters are provoked into adaptive planning for the long term health of the urban trees under their care.

Increasing temperatures and extended warm periods can stress street trees, especially during the dry summer months. Restricted planter spaces and the urban heat island effect exacerbate these issues and force urban forestry teams to water street trees. Trees placed in unrestricted grow spaces like parks are able to seek out moisture in the surrounding earth more easily than those placed in sidewalk cutouts. Unfortunately, lack of staffing and urban forest program funding made it so watering crews, for newly planted and annual street tree watering, were considered too costly by the City of Olympia (M. Bentley pers. comm. May 20, 2020). Consequently, no new street trees have been planted since 2015 because of these watering restrictions (M. Bentley, pers. comm. May 20, 2020). In effort to determine the most cost-effective watering methods for street trees, the City has taken on a Pilot Street Tree Watering Project whereby 30 trees were planted, watered, and studied to insure proper tree growth and watering methods can be used in the future (M. Bentley, pers. comm. May 20, 2020).

Increasing temperatures in mid-latitudes are altering the range of historic tree growth (USGCRP, 2018). This climate-induced shift in tree species affects the types of trees that have historically grown successfully in a given urban environment, and many urban foresters agree that urban forestry planning will require an innovative approach to species selection in the years ahead (M. Bentley, pers. comm. Jan. 16, 2020). In Olympia for instance, cedar, hemlock, and true fir tree species are showing signs of stress from changing climate conditions; tree species that currently grow well in Southern Oregon are being considered for street tree selection in Olympia because of their ability to thrive in more arid summer conditions (M. Bentley, pers. comm. Jan. 16, 2020). Additionally, urban foresters face the challenge of increased severity and range of pest infestations. Within Olympia cherry, ash, and hemlock tree species are no longer planted because of their susceptibility to infestation (M. Bentley, pers. comm. Nov. 24, 2019). Proactive urban forestry planning will be needed to support social and ecological health and safety in the face of such growing threats.

Urban forestry planning with a normative perspective of the many interconnected ecosystem services can provide a conceptual framework to reimagine our cities as we seek new ways to adapt to a changing climate. However, complex systems such as forests, even urban forests, are by their very nature webs of relationships that can be challenging to predict and manage. Even more difficult is attempting to assign economic values to the complexity of the natural world.

How valuable is a tree?

For the true nature of things, if we will rightly consider,
every green tree is far more glorious than if it were made
of gold or silver.

—Martin Luther King Jr.

Trees have embedded cultural and social values, but for many urban forestry departments, justifying the costs of tree maintenance and planting to local government requires a conversation about what is meant by a tree's "value". Many urban foresters need to defend the (sometimes high) costs of tree maintenance against the hard-to-quantify benefits of trees (Grant, 2012; Vargas, 2018). How do you measure the beauty of an old tree? How do you measure the benefits of the comforting shade from a sprawling oak tree?

Nevertheless, measuring the world around us and understanding the embedded systems within our natural world is the primordial soup from which every scientific discipline has emerged, grown legs, and established itself as a system of philosophical thought (Roszak, 1992). In order to defend urban trees as a component of green infrastructure within the city, scientists and urban foresters are rising to the challenge of measuring the complex and inter-relational benefits of trees, and including the metrics of monetary values to reflect our capitalist systems of value (Asselmeier et al., 2019; McPherson et al., 1994). In this section, I will consider how the value of Olympia's urban forest has been determined in the past, some of the current theories and challenges of placing value on elements of the natural environment, and how valuation may be improving with recent scientific research.

According to the Master Street Tree Plan the entire urban forest in Olympia was valued to be worth approximately $3,000,000 in 2006, and $6,100,000 by 2016, more than doubling in 10 years (CFC, 2016; Roush & McFarland, 2006). Conventional appraisal values for trees are determined by adding planting and replacement costs (in Olympia this would be $480 per tree) with values determined by the tree type and age as stated in the Council of Tree and Landscape Appraisers (CTLA) Guide for Plant Appraisal. However, systems of valuation do more than put a price-tag on a tree —they affect current and future city planning budgets and dictate urban forest management goals (B. Moulton, pers. comm. Feb. 13, 2020). On a deeper level, these systems reflect our societal philosophy on the worth of the environment and our obligation to its well-being.

Conventional attitudes about urban trees color how we perceive their value in the city environment, and, by extension, how we care for them. One of the most common tree maintenance requests received at the Urban Forestry department at the City of Olympia is for tree removal because sidewalk cracking, or tree limb removal in order to better see business signage from passing motorists on the street (M. Bentley, pers. comm. Jan. 16, 2020). Average annual spending for the Urban Forestry department in Olympia for tree and stump removal is almost $120,000, accounting for 25% of the total budget (Appendix B). These requests and subsequent city spending highlight how city residents and city officials see the role of trees in the urban environment--as problematic things to be removed. If we see trees as passive ornaments to adorn our streets and increase commerce in downtown areas rather than the dynamic living participants of the city's ecology, then we do not see their true inherent value.

It would seem at times that the man-made city and the ever-changing-ever-growing trees are at odds with one another. Conventional approaches to greenspace management and urban forestry have often focused on aesthetic amenities, tourism, and community enhancement (Pearlmutter et al., 2017; Roush & McFarland, 2006). For instance, the Downtown Strategy of Olympia included street trees as an important part of its plan for an aesthetic “continuity in the retail core,” while tree selection and placement focused on size and canopy shape, with consideration for the tree canopy to obscure business signage (Arai/Jackson Architects & Planners, 2003). Although economic benefits to tree landscaping of business districts has been shown to increase consumer spending by 11% on average, and the presence of trees has been shown to decrease crime rates and therefore can be seen as a social benefit (Hastie, 2003), these guiding principles for tree planting do not always work in the best interest for the tree’s long-term health.

It can be challenging, under even the best circumstances, for a tree to reach full maturity (therefore offering the most in ecosystem services to the community) in the middle of a city (Pearlmutter et al., 2017). Take, for instance, the tragic tale of the Legion Way trees in Olympia. Planted in 1928 to honor WWI and Spanish-American War veterans, they settled into gracious 12’ wide planting strips and over time becoming fully mature Oak and Sweetgum trees beautifying the Eastside, and generally beloved by the community. But in the 1980’s, on the north side of the street, an electrical power line hung dangerously close to the swaying leaves and branches of the growing canopies. Acting in an orderly fashion, Puget Power sent crews through and systematically topped (cutting off the top half) of each tree on the north side, a pruning tactic no longer used because of the damaging effect it has on the tree's growth, health and lifespan (CFC, 2016). In order to maintain a city greenspace aesthetic of uniformity, each tree along the south side was also topped, leading to years of malformation (Figure 4), tree death, and costly tree maintenance by the City of Olympia (CFC, 2016).

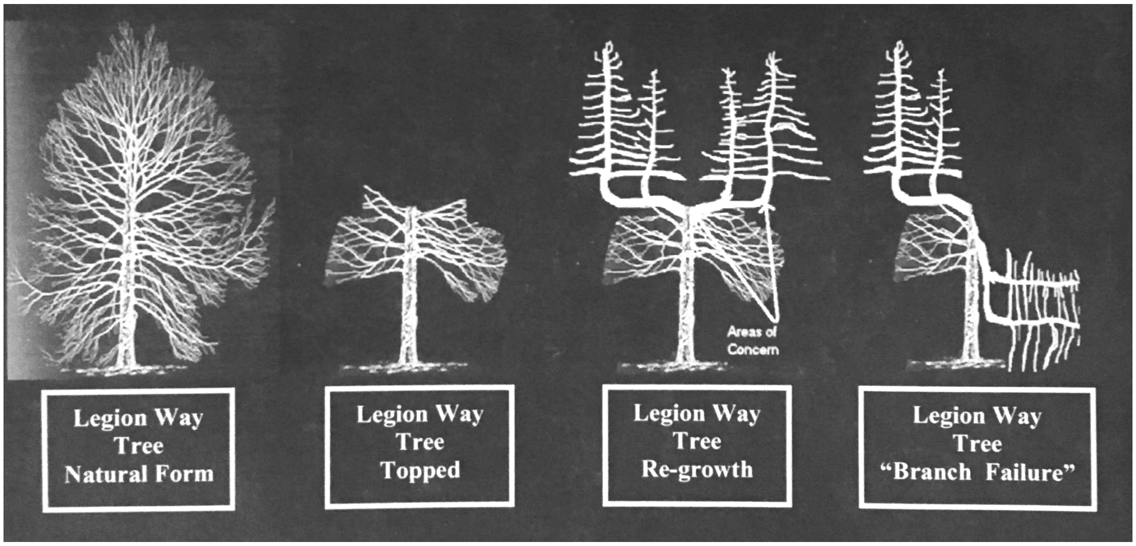


Figure 4. Legion Way tree "topping" diagram of effects on long term tree health and maintenance.

As a result of this approach to tree maintenance, the city now spends thousands of dollars every year to maintain the Legion Way trees (Allen-Ba, 2010). In 2010, the City spent $50,600 to remove and replant damaged trees on Legion Way. Expectedly, this figure does not include the inevitable loss of the ecosystem services these trees had provided to the surrounding neighborhood. Because the Eastside neighborhood meets the requirements of a low-income community, the City secured a $10,000 of grant funding from the Olympia Housing program in 2010 to remove five of the damaged trees (Allen-

Ba, 2010). While the City of Olympia has acted accordingly to plan for the care and resolution of the Legion Way tree situation, it is interesting to pull back a moment and consider the consequential economic dynamics happening here. In order to replace trees damaged by an energy company maintenance crew, the City sourced funding from the City of Olympia Housing and Social Service program.

As we can see from the Legion Way story, our value systems inform our actions, and it becomes necessary to recalibrate our systems of valuation to advocate for the long-term health of our urban trees, and for the benefits that come with having a healthy urban forest. Attempts to advocate on behalf of urban trees and the environment have come a long way in recent years, with experts and researchers working hard to create a system of valuation for natural processes in monetary terms (Hirabayashi, 2014; McPherson, 2010; US DOE EIA, 1998). Economic valuation can be an important part of advocating for program funding, urban planning priorities, or the enactment of policy.

One interesting example of economic valuation on aspects of the environment to advocate for new federal policy is the highly contested Social Cost of Carbon, a value attributed to the economic harm of carbon emissions and climate change (Cropper et al., 2018). This value not only represents the projected economic losses from climate change on agriculture and other industries, but also creates a price that can be used to support federal policy measures addressing the growing concern of climate change. The Social Cost of Carbon emerged from a continually evolving federal cost-benefit regulation that began under the Reagan administration in 1981 (Epa & Change Division, 2016).

In essence, the calculation involves projecting future population growth and greenhouse gas emissions, modeling the impacts of climate change, and calculating how the climate change models would affect the growth models and the economic costs associated with that growth. It has also been implemented in state efforts to create policy programs to lower emissions (Epa & Change Division, 2016). In 2020, the Social Cost of Carbon was estimated at $50 per short ton, the value can vary wildly with minor adjustments to the models and input values, and more importantly, with the change of political parties calculating these results. For example, in 2020, Executive Order 13783 amends the previous presidential executive order so that only domestic emissions are included at a reduced economic rate (Cropper et al., 2018). The adjusted rates reduce the previous $45 per ton to between $6 and even just $1 per ton. This diminution of associated Social Cost of Carbon reflects the political attitudes regarding climate change and the philosophical framework that informs federal and state policy (Cropper et al., 2018).

We still need to consider the benefits of trees that we cannot factor easily into our economic equations. It is well documented that trees reduce stress, improve health, reduce crime (Grant, 2012; McPherson et al., 1994; Pearlmutter et al., 2017), and although these important benefits do not easily factor into tree cost-benefit analyses, techniques for determining them continue to evolve, including the iTree urban forestry software.

Created by researchers at the Pacific Southwest Research Station’s Center for Urban Forest Research and funded by the USDA Forest Service, the iTree Suite is a software program specifically designed to aid urban foresters and tree advocates in determining the ecosystem services, associated social and economic benefits, as well as the structure of a city's tree population (Vargas, 2018). The results from iTree have been used to defend conservation, maintenance costs, and planting initiatives by attempting to calculate the social and economic benefits of trees (American Forests, 2008; Asselmeier, 2019; McPherson et al., 1994). I use "attempt" because the embedded algorithms in iTree are continually being improved and updated as new peer-reviewed science becomes available and researchers improve the techniques for determining how to measure the many benefits of trees (Hirabayashi, 2014).

I chose iTree Streets and iTree Eco as my tools for analysis of street trees' contribution to processing stormwater, reducing carbon emissions, improving air and water quality, and the health of Olympia City residents. In the following pages, we will explore the embedded models used in the iTree Streets and iTree Eco software, and show how both programs with GIS maps were used in this study to analyze the ecosystem benefits of Olympia's street trees.

METHODOLOGY

My research questions for this study are "what ecosystem services are offered by Olympia's street trees?" and "do the benefits provided by street trees outweigh the costs of their maintenance?" In order to answer these questions, I chose to use two different urban forestry support programs, iTree Eco and iTree Streets (developed by USFS) to determine annual environmental and fiscal benefits of street trees. Using the tree variables from the existing tree inventory and the most current regional data available, I ran both the iTree Streets and iTree Eco programs and compared the results. Concurrently with iTree software processing, geospatial analysis in ArcGIS was completed utilizing regional data and aerial imagery of Olympia to supplement and support the iTree program results. My research method can be summarized as occurring in four stages:

Stage I: Emission rates and regional data were collected. Data was then formatted for import into each of the iTree programs and GIS using Microsoft Excel. The data is broken down by topic in the following sections.

Stage II: iTree Streets and iTree Eco first draft runs were conducted and reexamined for data model improvements. Additional data collection and formatting was completed for final software reports.

Stage III: Geospatial analysis in ArcGIS Pro conducted using the tree inventory and raster imagery provided by the City of Olympia. An assessment of greater Olympia for tree canopy health and surface cover completed using ArcGIS Pro, and Esri Insight.

Stage IV: Final iTree Streets and iTree Eco reports were run and GIS maps analyzed to determine the ecosystem services provided by Olympia street trees. Results were then curated, compared, and published using Esri Storymaps.

Stage I: Emission rates and regional data

To determine mitigation costs and the monetary savings due to the presence of street trees in Olympia, I collected data to determine a baseline of regional costs. The collected data include an active tree inventory of 2,483 right-of-way street trees, as well as GIS tree locations and conditions sourced from the City of Olympia's Urban Forestry department. To add to the robustness of my study, LiDAR and satellite raster images of Olympia were geospatially analyzed to provide an assessment of surface types and tree canopy health. In the sections that follow, I have included short descriptions of the regional data types used, and the role each of these variables played in the process of determining street tree benefits. To see a complete list of exact values used for emission rates please see Appendix A, and for regional data, see Appendix B.

Emission rates

Local electricity rates were used to determine the average energy needs for the region in question, and imperative for defining the fossil emissions mitigated by the presence of street trees. I calculated the values by first determining consumer rates, and then factoring in the fuels used to generate the energy for the region. Currently Thurston County and the City of Olympia receive all their electricity and natural gas from Puget Sound Energy (PSE). Interestingly, as of 2016, coal accounted for 37% of PSE's fuel mix, natural gas accounted for 22% (2016), 31% was hydroelectric, while the remaining 10% came from wind and other energy efficient resources as illustrated in Figure 5. According to the Washington Utilities and Transportation Commission (UTC) the average PSE residential customer uses 1,000 kilowatt hours-per-month of electricity at a total cost of $102.56 and 68 therms of gas a month at a cost of $86.09 (Appendix A).

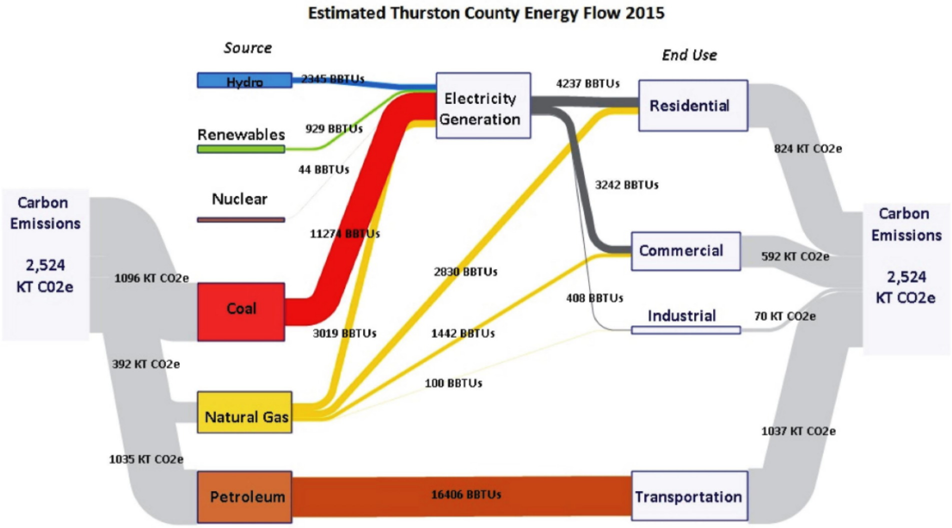


Figure 5. The 2015 Energy Flow Diagram: actual and estimated data obtained from Puget Sound Energy (electricity) and TRPC estimates (transportation).

Carbon dioxide values I sourced from the “Social Cost of Carbon in the US” estimates published by the EPA and other federal agencies (Epa & Change Division, 2016). The carbon cost plays a vital role in determining how many pounds of carbon emissions can be mitigated by the presence of trees, lowering other incurred costs such as medical expenses paid by city residents. Carbon values ranged widely between $12-$123 per ton of CO2 (Epa & Change Division, 2016). Based on the 2016 EPA carbon value converted to 2018 dollars (as recommended by iTree Eco) the cost of carbon used in this study is $170.55 per ton.

SO2, VOC, PM2.5, PM10, NO2 values were determined using EPA’s Environmental Benefits Mapping and Analysis Program-Community Edition software (BenMAP-CE). The BenMap-CE software program was designed to calculate the medical costs due to poor air quality. These medical costs help us understand how air quality improves in the presence of trees, thereby improving the health of local residents. Updated in 2018, the iTree Eco emission default values were used in this study (Appendix A).

Regional data

City layout data allows for the determination of landcover types in Olympia. The total area of impervious surfaces in the City and the amount of tree canopy can be input into iTree and GIS to help determine the ecosystem benefits of trees. Along with city size by square miles, variables included in this analysis were sidewalk and street dimensions, and tree planter types sourced from Olympia's 2018 Engineering Design and Development Standards (Appendix B).

Olympia urban forestry program expenditures: To conduct a cost-benefit analysis, a baseline of expenditures by the City of Olympia on behalf of the trees was needed. I collected the program expenditures from 2014-2019 were collected to find average annual costs. Unexpectedly, program expenses fluctuated over multiple years, varying from year-to-year. For example, irrigation expenses for newly planted trees were done only in 2015 and 2016, and storm litter cleanup expenses occurred for 2019 only. Therefore iTree programs were run using average program costs over five years (2014-2019) (Appendix B).

Identified tree variables used in iTree Eco, iTree Streets, and GIS included the following tree variables: species, crown width, total height, and DBH as seen in Figure 6, and growspace (planter type/size) data. I sourced this data from the tree inventory maintained by the City of Olympia Urban Forestry Department (Appendix C). The Olympia street tree inventory includes entries for either existing trees, planting sites, or tree stumps. Because this is an active inventory, this research provides a "snapshot" of all data fields from the street tree inventory

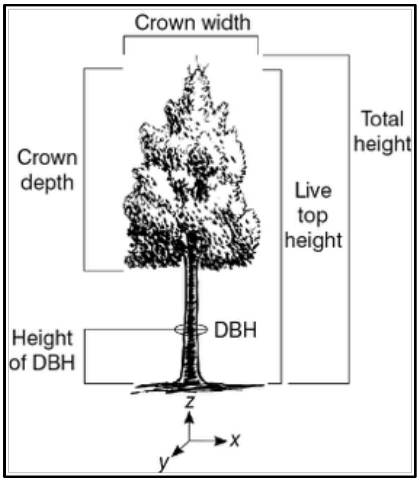


Figure 6. Tree meaurements diagram

at one point in time. For exact figures entered into iTree Streets and iTree Eco see Appendix B.

Land use types in Olympia make it possible to determine trends in street tree health based on the areas where they were planted. Land-use categories such as industrial, residential, and commercial, were collected and entered into iTree programs (Appendix C).

Stage II: iTree Analysis

The underlying models differ between the iTree Streets and iTree Eco programs in a number of significant ways. For instance, the variables required to determine energy benefits differ between the programs, and the stormwater model in iTree Streets is based on a different rainfall interception model than the iTree Eco models (Xiao et al 1998; Wang et al. 2008). **Water interception** is rainfall stored temporarily on tree canopy leaves, which then drips down the body of the tree, falls off the leaves into the ground, or is evaporated into the atmosphere. In addition, iTree Eco uses 2016 weather and pollution data, whereas iTree Streets models are based on weather information from 2006. For a further discussion on the differences of these models and their results, please see the results and discussion section.

iTree Streets software methodology

iTree Streets uses the Pacific Northwest climate region to determine the average rate of tree growth, average tree size, common tree species, and what leaf area is commonly measured for trees in the chosen climate zone. Regional tree models within iTree Streets are based on the study measurements from a regional reference city. **Reference cities** are chosen from each of the 16 climate zones to determine baseline tree growth, and climate conditions for that region as seen in Figure 7 (McPherson, 2010).

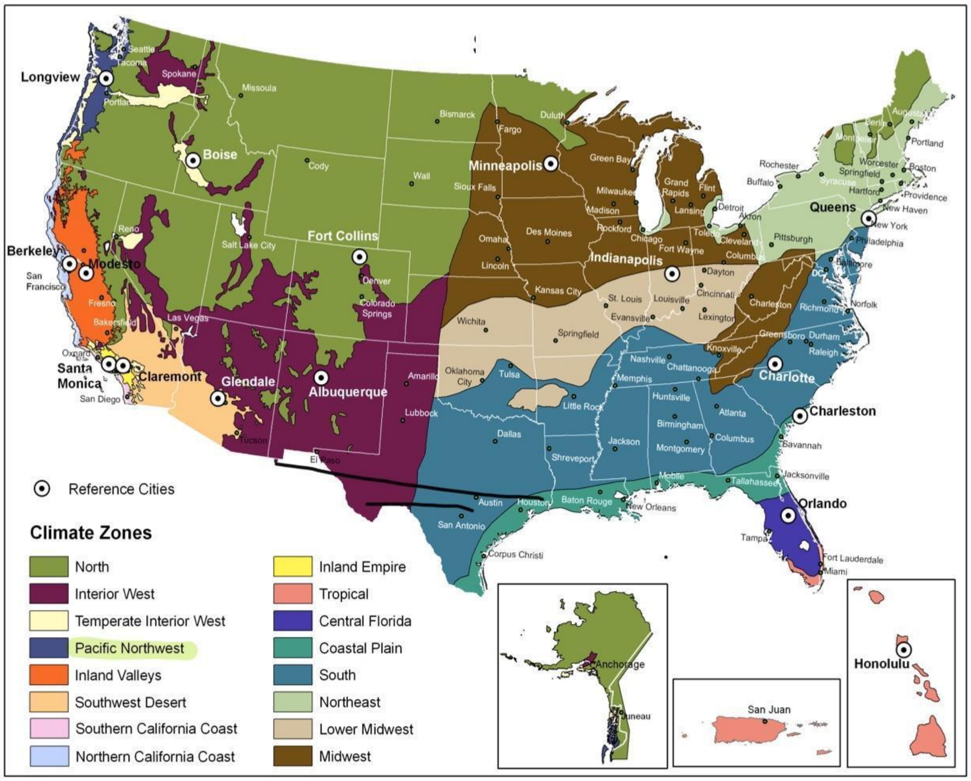


Figure 7. Climate zones used in iTree Streets to determine average tree growth rate data and climate conditions (Vargas, 2018).

In each reference city, 30 to 60 trees were chosen from 22 major tree species to be measured and aged to represent tree growth for the region (McPherson, 2010). Regression analyses of regional tree growth curves were conducted to determine the estimated tree benefits expected for each year of a tree's life cycle and to estimate tree leaf size index (Gregory et al., 2002; Vargas, 2018). The estimated values from each reference city are included as default values, which have been updated to reflect current regional values, as seen in Appendix A (Gregory, Qing fo, Scott, Maco, et al., 2002). The chosen reference city for the Pacific Northwest was Longview, Washington, conducted in 2006.

Longview is in the Pacific Northwest of Western Washington, about 60 miles south of Olympia, and has a population of 36,646 (as of 2010) and receives an average annual of 46 inches in rainfall. In comparison, Olympia has 51,609 residents and receives inches of 50 inches precipitation annually (Weather Atlas, n.d.). Average temperatures for Longview are 41° and 61° for winter and summer seasons respectively, and Olympia's mean winter temperatures are close behind at 38°, with summer temperatures averaging 64°. Although not an exact match, the use of Longview as the model for data analysis is, in this author's opinion, in range of acceptability as a city of comparison, and certainly better than using models based on national weather and climate data to determine such things as average tree growth and leaf area.

iTree Eco software methodology

Data from 2,346 trees were successfully imported using the iTree Eco software. iTree Eco uses tree canopy measurements to determine a tree's leaf size and biomass, and how these variables affect the ecosystem service estimates. The iTree Eco model decreases in accuracy with every missing tree variable required to run the reports. Because of unavailable inventory data, iTree Eco did not assign any ecosystem values for an additional 93 tree entries. In total, 2,253 trees were successfully analyzed using limited DBH and associated tree species data.

iTree Eco uses tree canopy variables to estimate energy savings, air quality, and stormwater benefits of trees. The Olympia tree inventory does not include data on the percent of crown missing, bottom canopy height, or crown width in two directions. For energy models, the direction and distance from the nearest building are required, which are not available using the existing tree inventory. Reports were generated for all ecosystem services using the minimal requirements for the program using the parameters of tree BDH, tree species, and tree condition as a percentage (Appendix C). iTree Eco model results are compared to iTree Streets results in the following chapter.

Stage III: ArcGIS Methods

I used ArcGIS Pro to determine the geospatial relationships of the urban landscape and the street trees, as well as to provide a visual aid for future street tree planting recommendations. For a simplified ArcGIS methodology workflow please see Appendix D. GIS data included for geospatial analysis are summarized below:

1. Tree locations and related data (species, size, growspace, and condition)
2. Raster images of Olympia (2015) and (2018) for leaf-on and leaf-off seasons
3. Surface land cover types (impervious surfaces)
4. Olympia building size and locations

Esri Insights Workbook was utilized to aggregate graphics on the tree inventory data. The functions were performed to assess trends in tree health and planter size, tree health and local land type such as business or industrial areas. Associations with DBH and planter size, and map of planter locations were also performed (Figure 8).

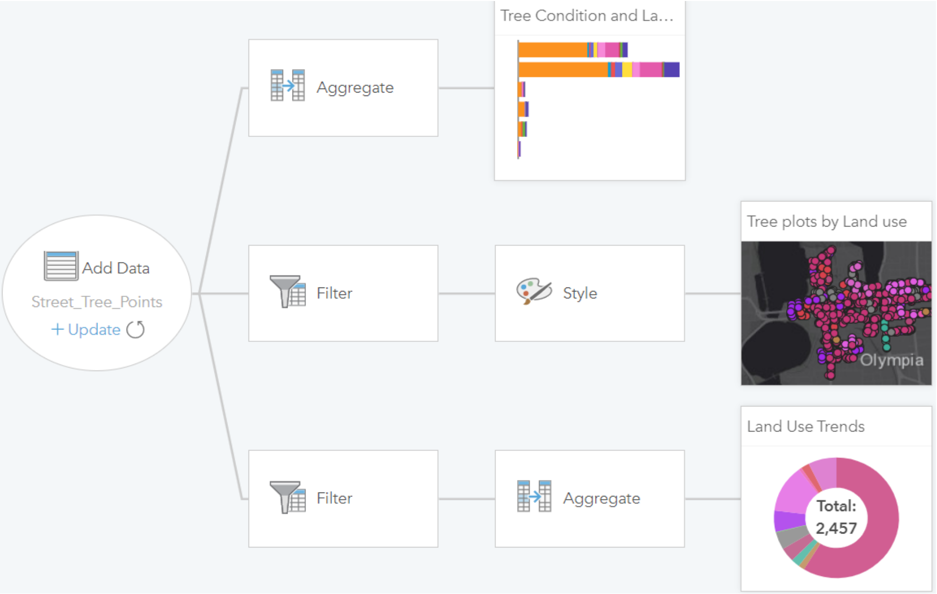


Figure 8. This workflow diagram illustrates the methods undertaken in GIS to analyze the urban forest structure using the City of Olympia's tree inventory dataset.

Using ArcGIS Pro a Heat Index function was performed using the aerial imagery obtained from the City of Olympia for 2018 to discern the heat response from different landcover surface types within the city boundary, focusing on the main arterials where street trees are planted and downtown Olympia. Heat maps are a visual assessment of the landscape that shows the cooling effects of vegetation, and the heat reflection of impervious surface types responsible for the heat island effect.

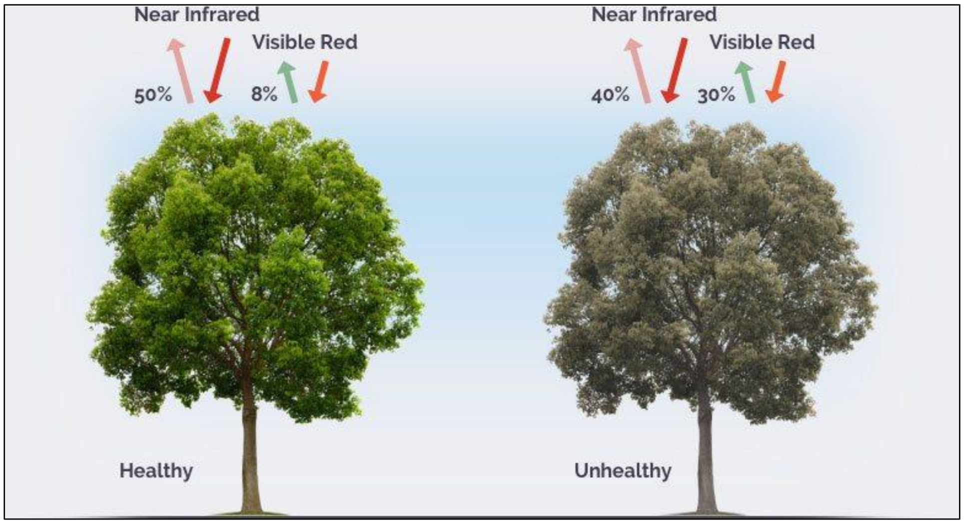


Figure 9. Diagram showing how satellite imagery sensors can detect leaf vitality using the near infrared response of healthy leaves using the Normalized Difference Vegetation Index (NDVI) (Earth Observing System, n.d.).

The canopy health of trees has been studied as a measure of their potential ecosystem benefits and overall tree health (Grant, 2012; Young, 2011). The aerial imagery from 2015 and 2018 were analyzed using Normalized Difference Vegetation Index (NDVI). NDVI is a GIS raster function for determining plant health, using remote imagery to detect a change in the near infrared response from vegetation as seen in Figure 9**.** NDVI was used to compare the canopy health of Olympia street trees in warmer months (leaf-on) to cooler months (leaf-off) and to compare the vegetation response of deciduous tree to nearby conifer trees during leaf-off seasons. The resulting maps are shown in the following section.

RESULTS

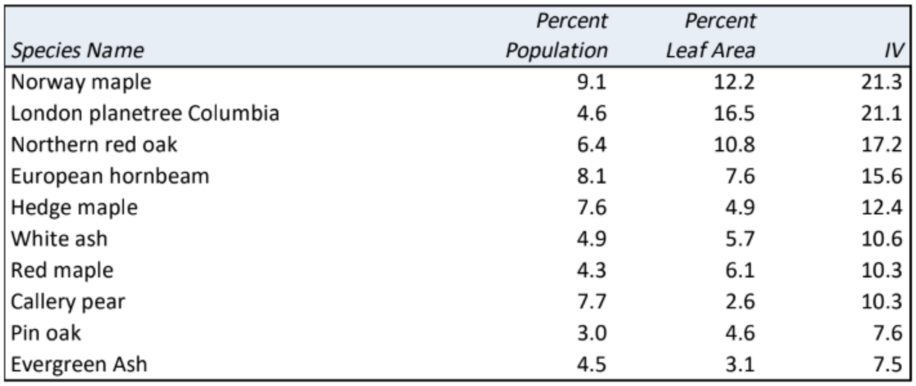
Utilizing the existing street tree inventory and both iTree Streets and iTree Eco programs I quantified and assigned dollar values associated with the annual ecosystem services benefits of Olympia's street trees. Results include values for forest structure, carbon storage and sequestration, air quality, energy, stormwater, and net benefits. I outline the results in this chapter, beginning with a discussion of Olympia's urban forest structure, followed by the iTree Streets results and iTree Eco results for street tree function and associated values. In the discussion I delve into the differences between the two models and the implications of their results. See Appendix E for a table of report results from both iTree Streets and the Eco program.

Urban Forest Structure

The iTree Streets and Eco results were in general agreement on the **forest structure** of Olympia's street tree population. The distribution of tree species, trunk sizes, and canopy area are all aspects of the forest structure and help urban foresters determine future goals for planting and maintenance. For the purposes of this study, these results help to establish the size, health, and makeup of the street tree population.

Olympia considers street trees as those planted in the public right-of-way, usually in the planting strip between sidewalk and road, or approximately 10 feet from the curb or roadside if a sidewalk is not present. The trees maintained by the City of Olympia's urban forestry department on a 3-year pruning cycle include 83 different tree species, the most common being Norway Maple, European Hornbeam, Flowering Pear, Hedge Maple, and Red Oak. These deciduous top five species currently account for 67% of the population as seen in Table 2**.**

Table 2. Ten most important species, collectively accounting for 60% of Olympia's street tree population.



Species Name	*Percent Population*	*Percent Leaf Area*	*IV*
Norway maple	9.1	12.2	21.3
London planetree Columbia	4.6	16.5	21.1
Northern red oak	6.4	10.8	17.2
European hornbeam	8.1	7.6	15.6
Hedge maple	7.6	4.9	12.4
White ash	4.9	5.7	10.6
Red maple	4.3	6.1	10.3
Callery pear	7.7	2.6	10.3
Pin oak	3.0	4.6	7.6
Evergreen Ash	4.5	3.1	7.5

iTree uses importance values to expand on how to determine the top ten species that dominate the Olympia inventory. **Importance Values** (IV) are calculated as the sum of the total species percent of the urban population and total percent leaf area as seen in Table 2. Collectively, the ten most important species make up 60% of Olympia's street tree population. Among these top ten species, the size distribution across the population as reported by iTree Eco is shown in Figure 10**.**

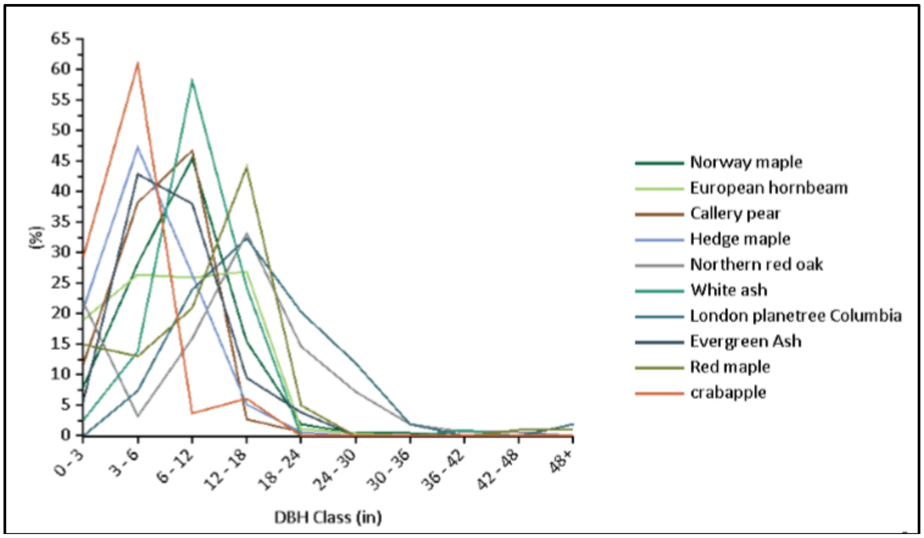


Figure 10. iTree Eco results for the top ten species sizes within the street tree population.

We can see in the iTree Streets diameter breast height (DBH) size distribution graph for the street tree population in Figure 11 that the trends tend to align with each other.

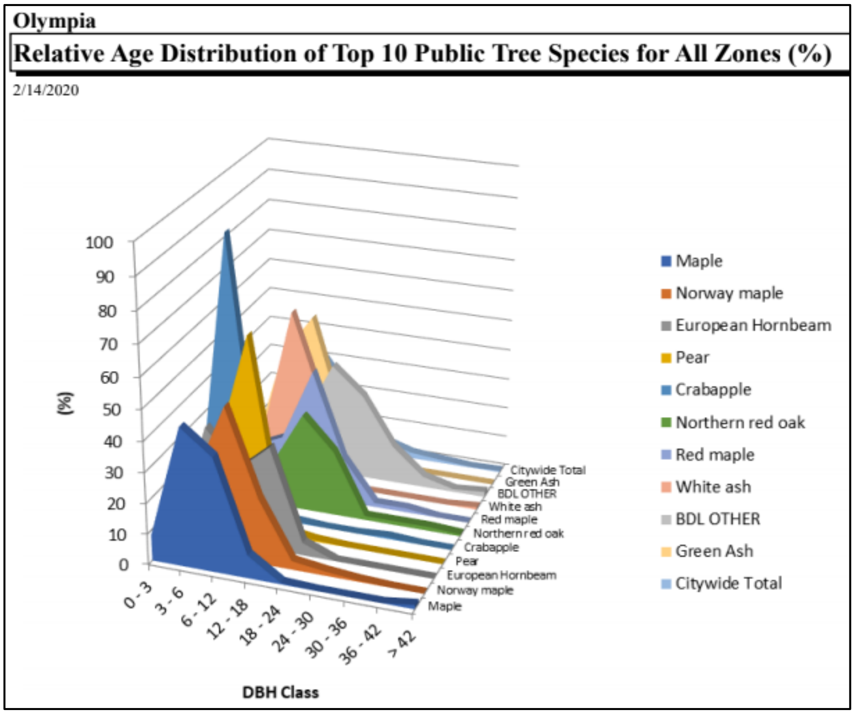
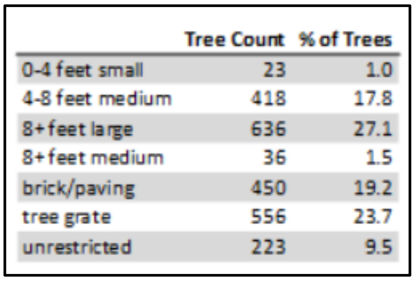


Figure 11. iTree Streets results for DBH distribution within the street tree population. Note that the BDL Other (Broadleaf Deciduous Large trees) category was attributed to tree species not recognized by iTree Streets.

Figure 11 shows a 3D graph illustrating the top 10 street tree species DBH classifications in Olympia as reported by iTree Streets , which supports the findings of iTree Eco on DBH distribution trends. As illustrated in both graphs, almost half of the population (46.5%) have a trunk DBH of less than 6-inches.

Table 3. iTree Eco tree growspaces



	Tree Count	% of Trees
0-4 feet small	23	1.0
4-8 feet medium	418	17.8
8+feet large	636	27.1
8+feet medium	36	1.5
brick/paving	450	19.2
tree grate	556	23.7
unrestricted	223	9.5

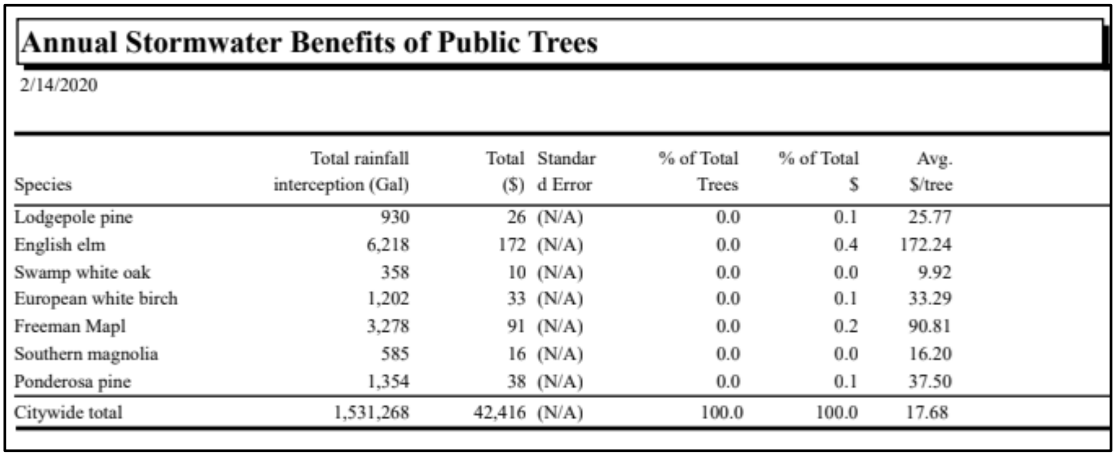
iTree Eco also reported the makeup of the growspace allotted to the street tree population (Table 3). Growspaces are planter types or growing spaces given to the street tree at a given location. As we can see from this report, smaller growspaces (4’x4’ tree grates, 0-4’ small, and 4’-8’ medium) make up more than 50% of the planting spaces. Which could account the small DBH trends for the street tree population.

The forest structure reports from both iTree programs lay the groundwork for better understanding the street tree population and helps us to become familiar with the layout of the iTree reports and the ecosystem service results we will see in the next section. Next, I will consider the results from first iTree Streets and then iTree Ecobefore concluding with GIS maps.

iTree Streets Software Results

As indicated earlier, I successfully imported data from 2,399 trees and analyzed them using the iTree Streets model developed by the U.S. Forest Service. I then conducted an assessment of the ecosystem benefits and associated values of the street trees, and cost-benefit analysis of tree costs and services, as outlined below.

Table 4. iTree Streets results for annual stormwater intercepted by species, and citywide total in gallons and dollars.



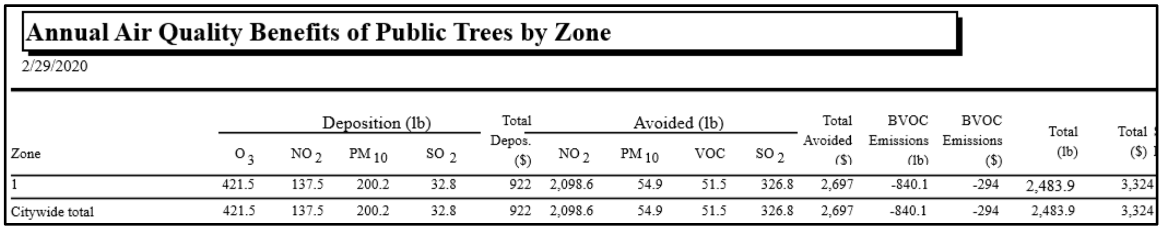
Annual Stormwater Benefits of Public Trees

2/14/2020

Species	Total rainfall interception (Gal)	Total ($)	Standard Error	% of Total Trees	% of Total $	Avg. $/tree
Lodgepole pine	930	26	(N/A)	0.0	0.1	25.77
English elm	6,218	172	(N/A)	0.0	0.4	172.24
Swamp white oak	358	10	(N/A)	0.0	0.0	9.92
European white birch	1,202	33	(N/A)	0.0	0.1	33.29
Freeman Mapl	3,278	91	(N/A)	0.0	0.2	90.81
Southern magnolia	585	16	(N/A)	0.0	0.0	16.20
Ponderosa pine	1,354	38	(N/A)	0.0	0.1	37.50
Citywide total	1,531,268	42,416	(N/A)	100.0	100.0	17.68

Stormwater: Determining the interception of rainfall by tree canopy was essential since my study involves a tree population that grows predominantly in confined urban growspaces with limited potential for soil infiltration of stormwater. In contrast to the iTree Eco stormwater results provided in the next section, the rainfall interception model of iTree Streets is more generous in its estimation of street tree stormwater benefits. As seen in Table 4**,** iTree Streets estimated total rainfall interception capabilities of street trees for this region at over 1,500,000 gallons per year. Using iTree Eco values for stormwater costs valued at $0.0277 per gallon (based on 2016 weather data and City of Olympia utility costs), I can estimate that street trees provide an annual savings of almost $42,500.

Table 5. iTree Streets results for annual air quality shown in total pounds of deposition (pollutants intercepted by the trees), total pounds avoided (energy emissions reduced thereby reducing air pollutants), and total biogenic volatile compound (BVOC) emissions (natural emissions from trees) here shown as a negative value.



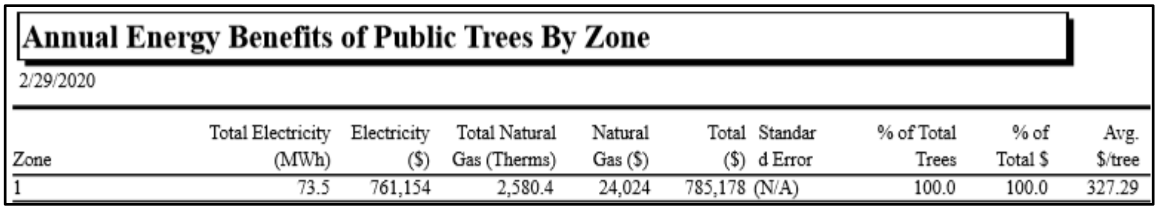
Annual Air Quality Benefits of Public Trees by Zone

2/29/2020

Zone	Deposition (lb)				Total Depos. ($)	Avoided (lb)				Total Avoided ($)	BVOC Emissions (lb)	BVOC Emissions ($)	Total (lb)	Total ($)
	O_3	NO_2	PM_{10}	SO_2		NO_2	PM_{10}	VOC	SO_2					
1	421.5	137.5	200.2	32.8	922	2,098.6	54.9	51.5	326.8	2,697	-840.1	-294	2,483.9	3,324
Citywide total	421.5	137.5	200.2	32.8	922	2,098.6	54.9	51.5	326.8	2,697	-840.1	-294	2,483.9	3,324

Air Quality: iTree Streets calculates the air pollution removal values based on the regional rates for health costs related to poor air quality (Vargas, 2018). Using the U.S. Environmental Protection Agency's Environmental Benefits Mapping and Analysis Program, I determined economic values for ozone, sulfur dioxide, nitrogen dioxide, and particulate matter smaller than 2.5 microns (Vargas, 2018) and input them into the iTree model. Based on the air pollution iTree Streets model, Olympia's street tree population intercepts and prevents almost 2,500 pounds of airborne pollutants every year, including nitrogen dioxide, sulfur dioxide, ozone, and particulate matter (PM10) (Table 5).

Table 6. iTree Streets results for annual energy savings citywide from the street trees shown as total savings of megawatt hours and dollars, and total savings of natural gas in Therms and dollars.



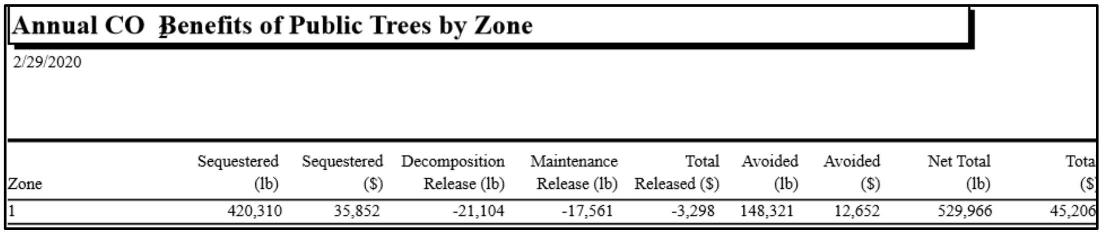
Annual Energy Benefits of Public Trees By Zone

2/29/2020

Zone	Total Electricity (MWh)	Electricity ($)	Total Natural Gas (Therms)	Natural Gas ($)	Total ($)	Standard Error	% of Total Trees	% of Total $	Avg. $/tree
1	73.5	761,154	2,580.4	24,024	785,178	(N/A)	100.0	100.0	327.29

Energy Benefits: The energy report in the iTree Streets model (Table 6) calculates the average benefits of trees from the Pacific Northwest region in terms of the energy demand reduction of nearby buildings (McPherson, 2010). The reduced demand of electricity is represented in total megawatt hours and as the sum of the megawatt hours multiplied with the local rate of $10.36/kWh (PSE, 2016). These secondary benefits result from trees shading buildings and nearby surroundings in the summer and protecting from wind in the winter. The values are based on the total estimated reduction in energy and the local sources of that energy, such as Puget Sound Energy's mixture of energy-producing fuels including coal, hydroelectric, and natural gas. The energy is broken down by dollar values per therms, kWh, or pound for a given resource. Exact figures can be found in Appendix A.

Table 7. iTree Streets results for annual carbon dioxide sequestration in pounds and dollars, and avoided emissions in pounds and dollars.



Annual CO$_2$ Benefits of Public Trees by Zone

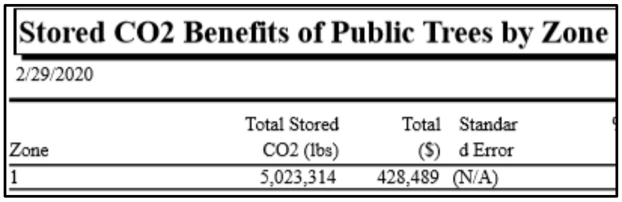
2/29/2020

Zone	Sequestered (lb)	Sequestered ($)	Decomposition Release (lb)	Maintenance Release (lb)	Total Released ($)	Avoided (lb)	Avoided ($)	Net Total (lb)	Tota ($
1	420,310	35,852	-21,104	-17,561	-3,298	148,321	12,652	529,966	45,206

Carbon dioxide: The Carbon Dioxide report presents annual reductions in atmospheric CO2 due to sequestration by trees and reduced emissions from power plants due to reduced energy use (reported here in pounds). Sequestration is the process of removing atmospheric carbon dioxide by plants and new plant growth. The model does account for CO2 released as trees die and decompose, and CO2 released during the care and maintenance of trees. Using iTree Streets I determined that Olympia street trees sequester roughly 210 tons (420,000 pounds) of atmospheric carbon dioxide with an associated annual savings of approximately $36,000 (Table 7).

Avoided carbon refers to the second-hand benefit of trees reducing building energy demands, thereby reducing the fossil fuel emissions from Puget Sound Energy by about more than 74 tons (148,000 pounds) each year, with an associated savings of about $13,000. In total, street trees remove 265 tons (530,000 pounds) of carbon annually, resulting in a savings of $45,000 every year to the City of Olympia (Table 7).

Table 8. iTree Streets results for the total stored carbon dioxide by the street trees in pounds and dollars.



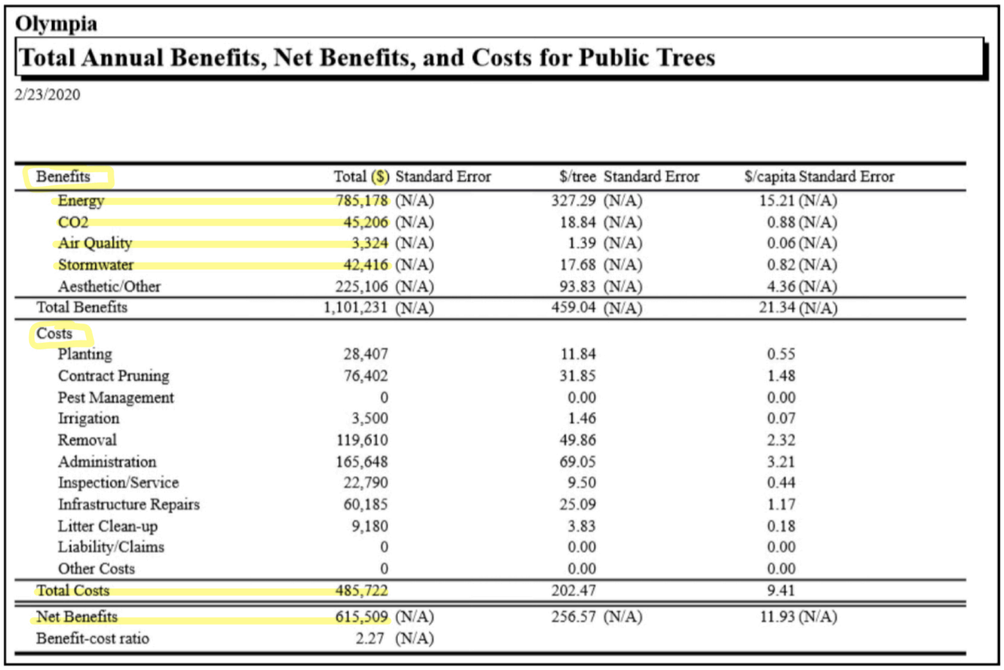
Stored CO2 Benefits of Public Trees by Zone

2/29/2020

Zone	Total Stored CO2 (lbs)	Total ($)	Standard Error
1	5,023,314	428,489	(N/A)

Carbon Stored: Whereas the above report quantifies annual CO2 reductions, the Carbon Stored report accounts for all of the carbon dioxide stored in the urban forest over the life of the trees as a result of sequestration (in pounds). These values were not added to the Carbon Dioxide value to avoid double-counting. Taken together, the CO2 avoided and carbon stored values remind us of the important role trees play in keeping greenhouse gases out of the atmosphere and thereby helping to mitigate local climate change stressors. To date, Olympia's street tree forest has stored more than 2,500 tons (5,023,314 pounds) of carbon, with an associated value of $430,000, as seen in Table 8 (EPA, 2016).

Table 9. Report of the annual cost-benefit breakdown for Olympia. As shown, the overall net ecosystem service benefits surpass the costs of tree maintenance.



Olympia

Total Annual Benefits, Net Benefits, and Costs for Public Trees

2/23/2020

Benefits	Total ($)	Standard Error	$/tree	Standard Error	$/capita	Standard Error
Energy	785,178	(N/A)	327.29	(N/A)	15.21	(N/A)
CO2	45,206	(N/A)	18.84	(N/A)	0.88	(N/A)
Air Quality	3,324	(N/A)	1.39	(N/A)	0.06	(N/A)
Stormwater	42,416	(N/A)	17.68	(N/A)	0.82	(N/A)
Aesthetic/Other	225,106	(N/A)	93.83	(N/A)	4.36	(N/A)
Total Benefits	1,101,231	(N/A)	459.04	(N/A)	21.34	(N/A)
Costs						
Planting	28,407		11.84		0.55	
Contract Pruning	76,402		31.85		1.48	
Pest Management	0		0.00		0.00	
Irrigation	3,500		1.46		0.07	
Removal	119,610		49.86		2.32	
Administration	165,648		69.05		3.21	
Inspection/Service	22,790		9.50		0.44	
Infrastructure Repairs	60,185		25.09		1.17	
Litter Clean-up	9,180		3.83		0.18	
Liability/Claims	0		0.00		0.00	
Other Costs	0		0.00		0.00	
Total Costs	485,722		202.47		9.41	
Net Benefits	615,509	(N/A)	256.57	(N/A)	11.93	(N/A)
Benefit-cost ratio	2.27	(N/A)				

The cost benefit analysis of iTree Streets breaks down the total annual values for tree ecosystem service (estimated at more than $1 million) and the associated cost for tree maintenance by the City of Olympia (an average of $486,000 in annual expenses). It then compares the total costs to the total ecosystem benefits of street trees to find the annual net benefits of Olympia's street trees: a collective worth of approximately $616,000 (Table 9). Each tree, therefore, provides an estimated gross annual ecosystem service worth $450. Accounting for tree maintenance costs, this equals $260 in net value for each tree every year.

iTree Eco Software Results

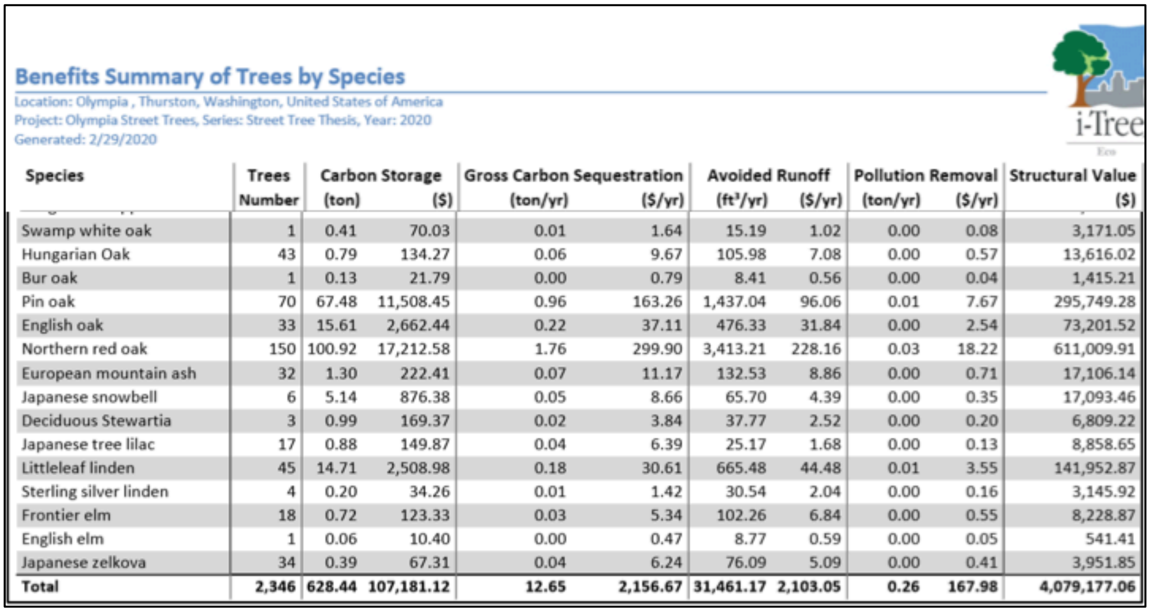
Because iTree Eco required tree data that was not included in the Olympia inventory, and because the inventory data entered into the software did not match all program requirements, the results from iTree Eco on air pollution, stormwater, and energy savings are considered by this author to be inconclusive. In this section I expand on the difference in software models and why I have come to this conclusion.

Compared to iTree Streets, the iTree Eco software models rely on more recently published tree ecosystem-benefit research and on 2016 weather information, but not all of the values required for "existing inventory import" were available. I imported the Olympia Street Tree inventory as the "existing tree inventory", limiting the number of tree variables analyzed because not all the iTree Eco software inventory import requirements were met using that data. Because of missing data, 93 tree entries within iTree Eco showed an ecosystem benefit value of *zero* for all reports in the results. That means that iTree Eco analyzed 146 fewer trees than iTree Streets using data from the existing Olympia tree inventory. This partially explains why the results of the iTree Streets and iTree Eco software programs were different in their values (Appendix E). For example, one of the most striking differences was the Net Benefits totals. For example, the iTree Streets model estimated the total ecosystem benefits provided by the street trees to be worth more than $1,100,000, whereas the iTree Eco model valued the benefits to be merely $4,427 (Appendix E). Understanding the different energy models of iTree Eco and iTree Streets can further our understanding of why the two programs have diverging net benefit results.

First, I will expand on the problems with the iTree Eco required “Crown Health Condition” parameters, measured on a scale of 0-100% (Appendix C). The existing Olympia inventory does not include a crown health field; instead, it includes an *overall* tree health variable, measured on a qualitative scale of “dead” to “excellent” with associated coded values (Appendix C**)**. I initially considered this field a potential substitute for crown health, but according to the GIS specialist for the Urban Forestry department, Woody Schaufler, the coded values are not necessarily an indication of the tree's health in terms of a percentage (W. Schaufler, pers. comm. Mar. 5, 2020). This is because the assignment of tree health conditions are applied by tree maintenance crewmembers as a subjective assessment of overall tree health (B. Moulton, pers. comm. Feb. 13, 2020).

The ability to gauge the health of the tree canopy affects the validity of the iTree Eco results because Eco determines ecosystem services (such as carbon sequestration, air quality, energy savings, and stormwater benefits) by the health and dimensions of each tree canopy. Therefore each report shown below has been scrutinized to determine the credibility for this study and found that the carbon sequestration, air quality, energy savings, and stormwater benefit reports were unreliable based on the current Olympia inventory attributes used in this study.

Table 10. Excerpt from iTree Eco results for street tree benefits (ex. carbon storage and sequestration) by tree species.

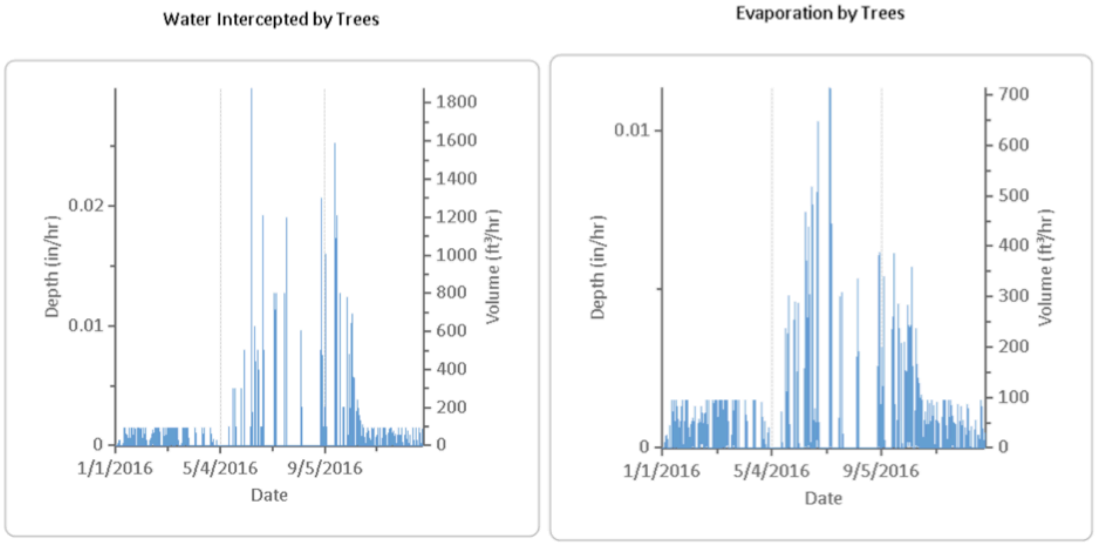


Benefits Summary of Trees by Species

Location: Olympia , Thurston, Washington, United States of America
Project: Olympia Street Trees, Series: Street Tree Thesis, Year: 2020
Generated: 2/29/2020

Species	Trees	Carbon Storage		Gross Carbon Sequestration		Avoided Runoff		Pollution Removal		Structural Value
	Number	(ton)	($)	(ton/yr)	($/yr)	(ft³/yr)	($/yr)	(ton/yr)	($/yr)	($)
Swamp white oak	1	0.41	70.03	0.01	1.64	15.19	1.02	0.00	0.08	3,171.05
Hungarian Oak	43	0.79	134.27	0.06	9.67	105.98	7.08	0.00	0.57	13,616.02
Bur oak	1	0.13	21.79	0.00	0.79	8.41	0.56	0.00	0.04	1,415.21
Pin oak	70	67.48	11,508.45	0.96	163.26	1,437.04	96.06	0.01	7.67	295,749.28
English oak	33	15.61	2,662.44	0.22	37.11	476.33	31.84	0.00	2.54	73,201.52
Northern red oak	150	100.92	17,212.58	1.76	299.90	3,413.21	228.16	0.03	18.22	611,009.91
European mountain ash	32	1.30	222.41	0.07	11.17	132.53	8.86	0.00	0.71	17,106.14
Japanese snowbell	6	5.14	876.38	0.05	8.66	65.70	4.39	0.00	0.35	17,093.46
Deciduous Stewartia	3	0.99	169.37	0.02	3.84	37.77	2.52	0.00	0.20	6,809.22
Japanese tree lilac	17	0.88	149.87	0.04	6.39	25.17	1.68	0.00	0.13	8,858.65
Littleleaf linden	45	14.71	2,508.98	0.18	30.61	665.48	44.48	0.01	3.55	141,952.87
Sterling silver linden	4	0.20	34.26	0.01	1.42	30.54	2.04	0.00	0.16	3,145.92
Frontier elm	18	0.72	123.33	0.03	5.34	102.26	6.84	0.00	0.55	8,228.87
English elm	1	0.06	10.40	0.00	0.47	8.77	0.59	0.00	0.05	541.41
Japanese zelkova	34	0.39	67.31	0.04	6.24	76.09	5.09	0.00	0.41	3,951.85
Total	**2,346**	**628.44**	**107,181.12**	**12.65**	**2,156.67**	**31,461.17**	**2,103.05**	**0.26**	**167.98**	**4,079,177.06**

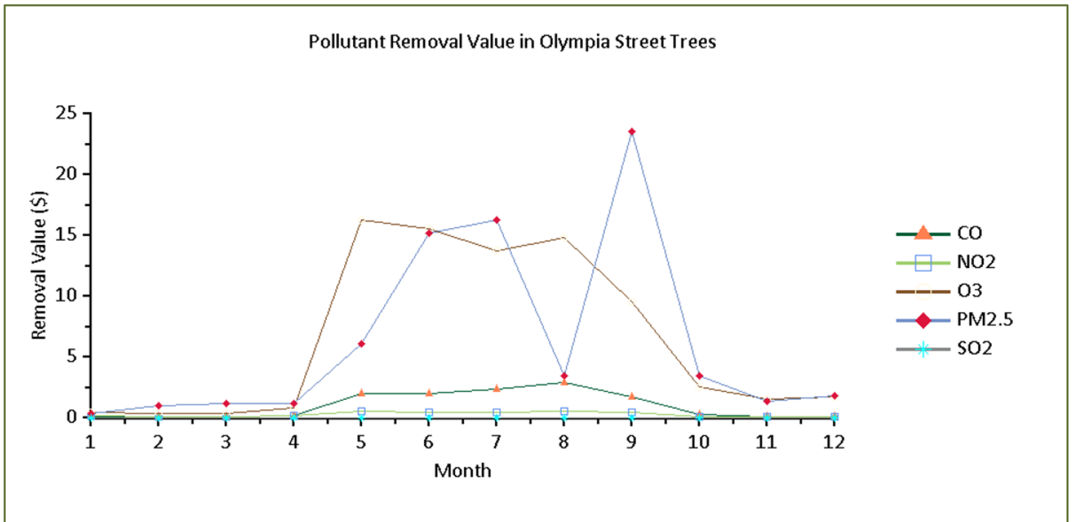
Carbon storage and carbon sequestration values were calculated in iTree Eco derived from the EPA Social Cost of Carbon value of $171 per ton (Forest Service, 2020). The sequestering of carbon by trees involves the absorption of atmospheric carbon dioxide by tree vegetation. Carbon storage is the amount of total carbon stored in the above-soil *and* below-soil parts of trees over the life of the tree. To determine the current carbon storage of Olympia's street trees, the biomass for each tree was calculated using embedded equations (based on iTree source literature) and measured tree DBH from the tree inventory (Forest Service, 2020). Of the street tree species in Olympia, Northern red oak stores and sequesters the most carbon: approximately 16.1% of the total carbon stored and 13.9% of all sequestered carbon. According to iTree Eco software models, Olympia street trees sequester 13 tons of atmospheric carbon during the annual growth cycle, as seen in Table 10.


Water Intercepted by Trees

Evaporation by Trees

Figure 12. Water interception and evaporation provided by trees per month for the weather data year of 2016.

Water intercepted reflects the amount of rainfall that fell on plants and was intercepted by the plant's leaves. This water eventually evaporates into the atmosphere. **Evaporation** is the amount of water that is released to the atmosphere from vegetation. Figure 12 displays of the hourly evaporation by trees. These results are based on what's referred to as a **conservative stormwater interception model** estimate of stormwater dynamics provided by iTree Eco. Conservative stormwater calculations depend on crown health variables to determine the amount of precipitation intercepted by the leaves only. This approach excludes the ability of tree stems and branches to intercept water. Because Olympia's tree inventory did not have the canopy variables required and only data for species and DBH were entered, the model relies on national averages to estimate canopy conditions. Therefore I do not consider the stormwater volume results to be credible in this study. It can, however, provide insight into seasonal tree behavior in stormwater processing potential. For example, Figure 12 shows the amount of evaporation trees provided annually as inches per hour, illustrating the vast increase in evaporation during warmer months, helping to cool the urban landscape as a consequence. As we can see, the estimated stormwater interception is fairly low in leaf-off seasons for deciduous trees and high during leaf-on seasons. We can also begin to see the repeating pattern of seasonal tree benefits as seen in the air pollution trends model (Figure 13) which both utilize local weather data embedded in ECO.



Pollution removal value is calculated based on the prices of $0.66 per pound (CO), $0.21 per pound (O3), $0.03 per pound (NO2), $0.01 per pound (SO2), $13.17 per pound (PM2.5).
A value of zero may indicate that ancillary data (pollution, weather, energy, etc.) is not available for this location or that the reported amounts are too small to be shown.

Figure 13. iTree Eco results for monthly pollutant removal trends by Olympia's street trees.

Air quality benefit trends of trees are shown in Figure 13. Trees intercept air pollutants (such as PM2.5) with their leaves. However, tree canopy variables and the distance and direction of trees to buildings did not exist in the Olympia street tree inventory data. According to the iTree Streets results, the total pounds of avoided emissions of air pollutants exceeded the total pounds of air pollutants intercepted by tree canopy. That indicates that the energy benefit model in iTree Eco is needed to determine the missing air quality benefits. Therefore, the estimated air quality results (in pounds and dollar values) are incomplete and inconclusive using iTree Eco. Much like the stormwater results, however, the line graph in Figure 13 can illustrate trends in providing air quality benefits according to local weather data and leaf-off seasonality. For example, the ozone (O3) pollution removal rates rise dramatically in the summer (around May) as a consequence of new canopy growth, and trees continue to provide air quality services until August when the ability of trees to intercept air pollutants drops down considerably as the leaves begin to fall away.

Energy: To calculate tree energy benefits, iTree Eco requires the input of each tree's canopy fullness (as a percentage), canopy dimensions, distance in feet to the nearest building, and the location of the tree to the building (NW, SE, etcetera). Because the City of Olympia personnel did not collect these variables for their street tree inventory, I could not run the energy benefits report in iTree Eco. In contrast, the model used to determine the energy-saving benefits in iTree Streets employs an average for all trees, regardless of their proximity to a structure. Those results are included in this study. The iTree Eco guidelines for collecting this information was, however, used in GIS to determine how many of Olympia street trees are providing some form of energy benefits to buildings. In the following section, I outline my GIS results on potential energy effects, cooling benefits, and canopy health.

ArcGIS Results

In this section, I present GIS maps to see how they supplement the limitations of both of the iTree programs and expand our understanding of the ecosystem services of Olympia’s street trees.

Energy Maps: In order to expand on the estimated street tree energy-benefits from iTree Streets and supplement the unavailable results for energy-benefits using the iTree Eco software, I assessed the potential of street trees using aerial imagery and city data of businesses and hard surfaces, as seen in Figure 14.

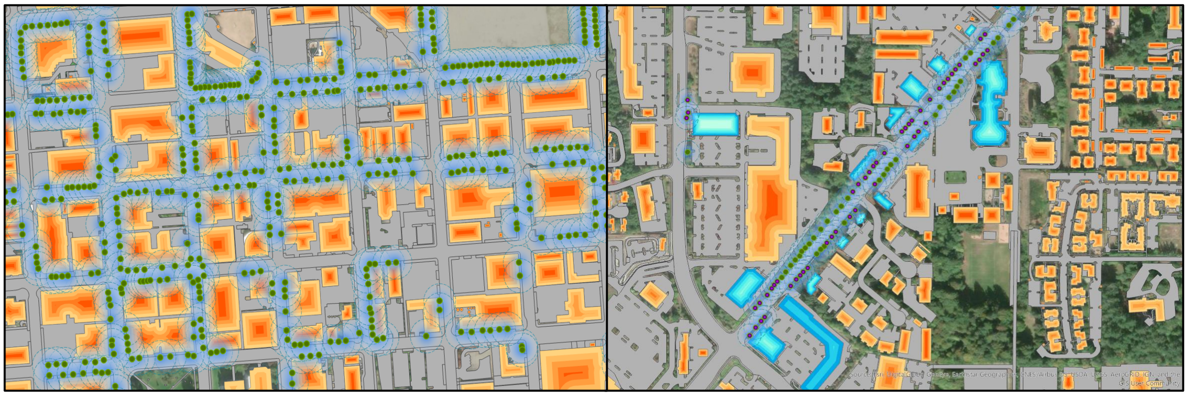


Figure 14. Tree locations are shown in green and buildings are shown in orange. The halo around each tree represents the 60-foot buffer which has been used as a measure of a tree’s effect on nearby structures for reducing energy demands.

Following the logic of buildings receiving energy benefits from nearby trees, I selected all trees (normally green dots) within 60-feet from a building and color-coded them in purple as seen in Figure 14. I then selected all buildings (normally orange) within 60-feet from a tree and color-coded them in blue, representing all the buildings being cooled by trees in warm summer months. These maps help us better understand the relationship of street trees to buildings and hard surfaces. Based on this geospatial analysis, I could determine that 72% of the street trees in Olympia (1,692 out of 2,334 live trees) are within range to alter energy demands in nearby buildings. I could also determine that 673 buildings in Olympia benefit from the proximity of street trees. (Note: This analysis accounts for only the street trees and does not account for any other surrounding trees.) I also used GIS to supplement iTree results and analyzed Olympia's street tree canopy health, which is linked to air-quality and stormwater benefits, as outlined below.

Heat Response: In addition to the tree and building spatial assessment done in GIS, I also performed a Heat Index analysis in GIS using aerial imagery of the City of Olympia (Figure 15), showing the response of landcover surface types to heat. This map illustrates the heat-response of building and hard surfaces to heat (shown in orange and red), and the relationship of trees and the temperature (shown in shades of blue) of their surrounding environment.

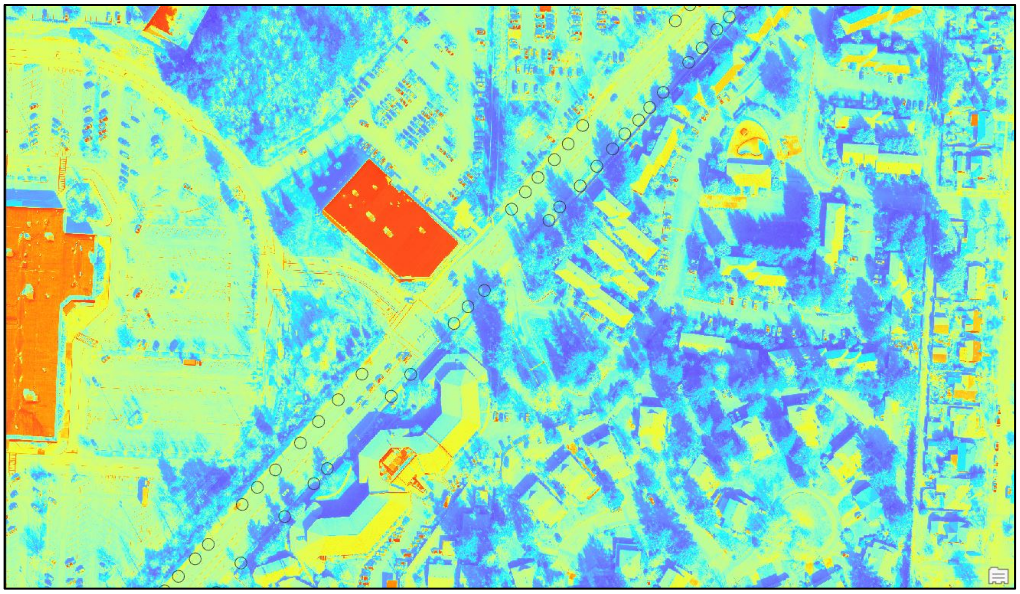


Figure 15. Heat Index GIS map showing the Downtown Olympia area and the heat response of buildings in bright red and orange, and the tree locations shown in the black circles. This image demonstrates the cooling potential of street trees in dense urban areas like Olympia.

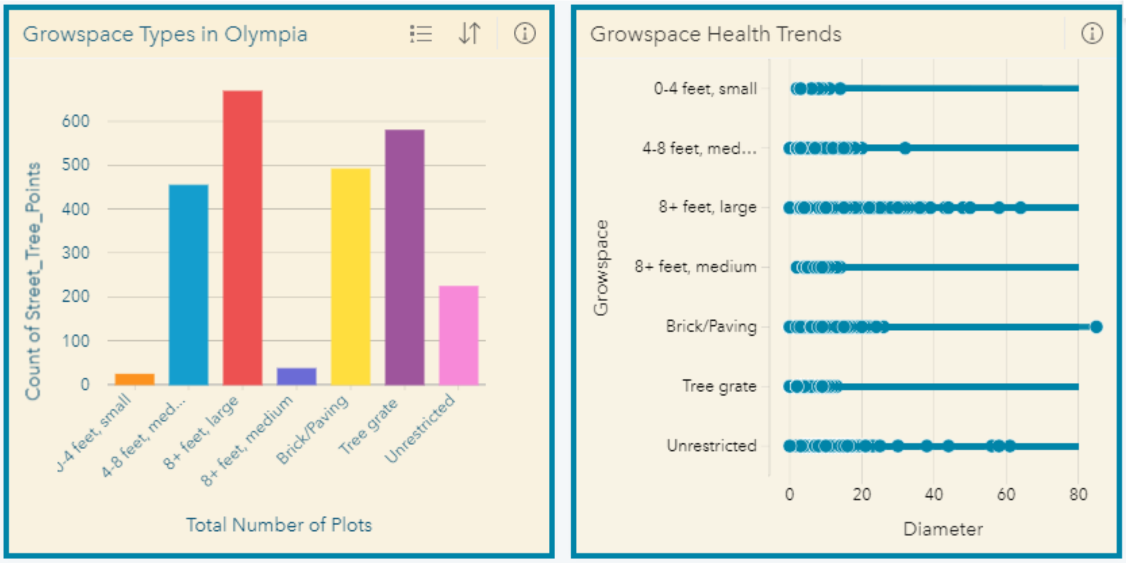
This cooling effect is one of the main arguments of the energy benefit phenomena, and has the secondary benefit of mitigating the urban heat island effect. As seen in Figure 15, the heat response of the landscape in areas with more canopy cover and pervious landcover types show a lower temperature response.

Figure 16. GIS NDVI raster image of Legion Way showing the near-red infrared response (red color) from vegetation during the Winter (leaf-off) season. The dark circles indicate where street trees are located.

Stormwater and air quality: The normalized difference in vegetation index (**NDVI**) assessment results show the health of the vegetation in Olympia in both winter and summer months. I used this analysis to visually assess the difference between the canopy cover of deciduous to conifer trees in leaf-off seasons, and to determine how these visual assessments compare to the iTree results for estimated ecosystem benefits for stormwater and air quality. The red color (near-infrared response) in the 2015 leaf-off winter season image shown in Figure 16 highlights vegetation with active chlorophyll production in red; in this case conifer species and ground-cover appear in red whereas the deciduous street tree locations (indicated by the black circles) show no-to very little response.

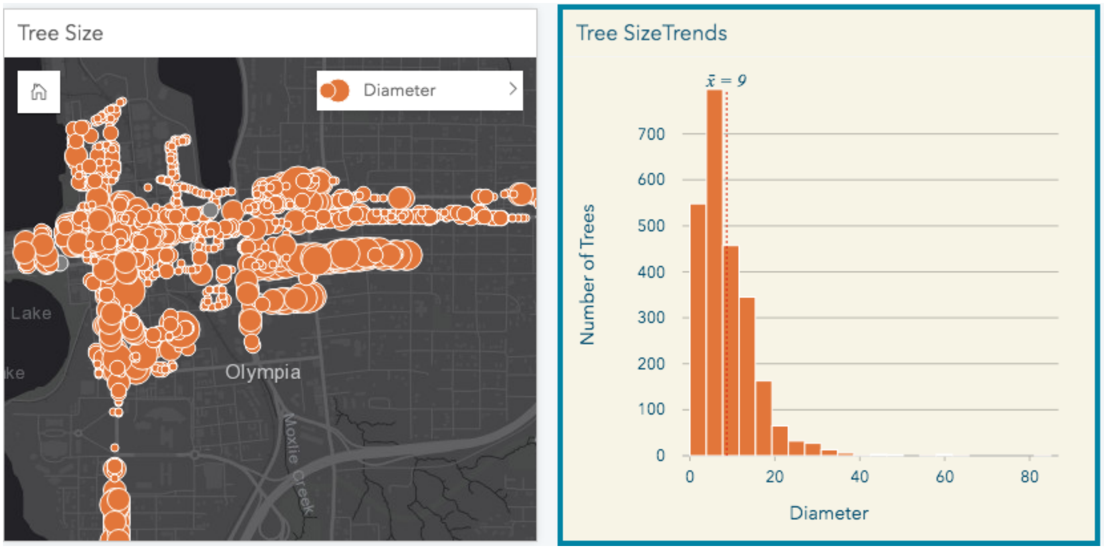
Figure 17. Planting sites (growspace) examples of street trees in Olympia. From left to right; 4’x8’ tree grate, 4x4’ tree grate, parking lot, unrestricted growspace.

Esri Insights for tree sizes and planter types: It is widely recognized in the literature that larger healthier trees provide greater ecosystem benefits, including stormwater infiltration abilities (Berland et al., 2017; Szota et al., 2019). I used Esri Insight Workbooks to consider the population of Olympia’s urban forest and the planting site types used to estimate infiltration. I looked at the planter types of Olympia’s trees and found that large 8+ feet planting sites were the most common. More large trees (based on DBH) grow in unrestricted and 8+ feet planter sites than in the other planter types, as seen in Figure 18. Unrestricted and 8+ feet planters comprise 37% of the active tree sites. The second most common planter type is the tree grate, which is 4’x4’ cement planter, and the DBH of trees in these locations do not exceed 18”. Planter types that are 0-4’, 4’-8’ medium, and 4’x4’ tree grate make up 44% of the active tree sites with DBH on average measuring less than 20”.


Growspace Types in Olympia

Growspace Health Trends

Figure 18. ArcGIS Insights results for growspace trends and relative DBH distributions of street trees.


Tree Size

Tree SizeTrends

Figure 19. ArcGIS Insights results for DBH trends showing the location and sizes of the street trees.

The bar graph in Figure 19 shows that the mean DBH in Olympia's street tree population is 9 inches and most trees have small DBH, mirroring the forest structure results from both iTree programs. The map to the left of the bar graph shows the locations of trees by circle size based on associated DBH measurements. These results could help the City of Olympia determine urban zones with either high or low potential ecosystem services by trees, based on associated DBH trends for the area.

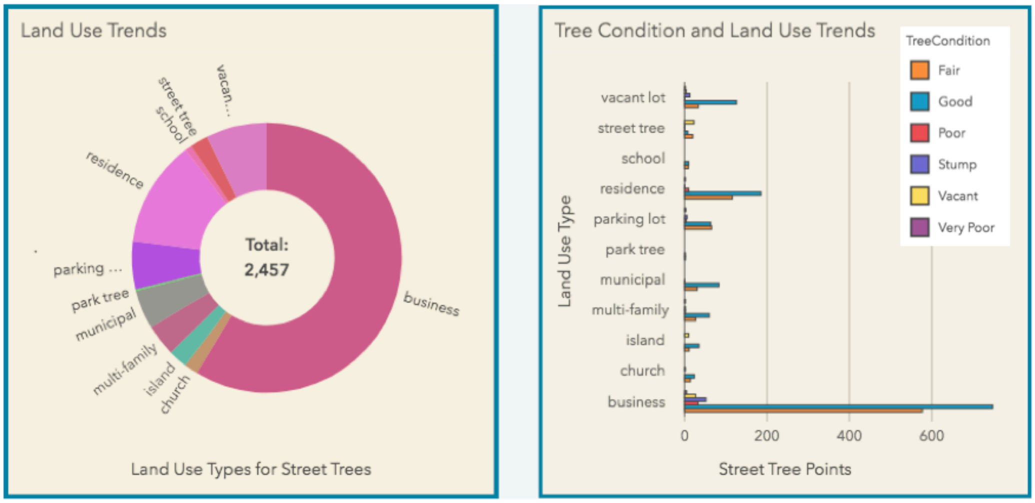


Figure 20. ArcGIS Insights results for Land Use and Tree Condition trends

The land use trends from Esri Insights show that street trees in Olympia have been planted predominantly in business areas (as seen in Figure 20), and the trees recorded as good condition are found predominantly in business land use areas. Therefore ecosystem benefits in business land-use types such as energy savings, and air pollution would be important to consider for both social and economic reasons.

Olympia's Urban Forest

An assessment of the ecosystem benefits of street trees in Olympia Washington using iTree and GIS software

Figure 21. Outreach and education storymap using Esri Storymaps: https://storymaps.arcgis.com/stories/791052f6bbd84edd8e3991fe42a437fd

Educational Storymaps: I created a story map using Esri Online for educational purposes and to share the study results with the City of Olympia’s urban forestry department, Thurston County, and publically to Olympia residents. The story map narrates the study using excerpts from this thesis, infographics, iTree reports, and GIS maps to highlight how street trees in Olympia provide an array of ecosystem benefits. This format allows the user to freely interact with the various GIS maps made in this study, and to get a more simplified summary of the results of this study.

DISCUSSION AND RECOMMENDATIONS

When one tugs at a single thing in nature
he finds it attached to the rest of the world.

— *John Muir*

As indicated earlier in this thesis, urban forests are complex living systems within our urban landscapes that interact with the environment by a process of equally complex exchanges. It is therefore a challenge to measure the many benefits they provide in quantitative and monetary terms for our purposes of urban planning and study. However, by using city tree inventory data, regional satellite imagery, and urban forestry tools such as iTree, we can better understand these systems and the contribution of street trees to environmental and public health. In the pages that follow, I discuss the iTree Streets and iTree Eco results, and GIS maps in more depth and how these findings shed light on the social, environmental, and economic benefits to the City of Olympia and its residents. The research results outlined in this chapter illustrate how Olympia street trees support the goals outlined in the Thurston Climate Mitigation Plan and the City of Olympia's Stormwater Management Program (SWMP) Plan, and the importance of further research on trees as a nature-based solution for climate mitigation planning. At the close of this chapter I have included a discussion of my study limitation and recommendations for future research on the ecosystem services of our urban forest.

Street trees and carbon services

Carbon storage capabilities by trees are widely recognized, with trees accumulating carbon in their woody material above and belowground over their course of their lifetime (Mcpherson et al., 1997; Nowak et al., n.d.). In developed landscapes, an urban forest can behave as a carbon sink, absorbing more atmospheric carbon than it emits (TRPC, 2017). Olympia's street trees have collectively stored roughly **5 million pounds** of carbon, according to iTree Streets results. When using the monetary values as determined by the EPA for the Social Cost of Carbon, this equates to a value of **$430,000** (Epa & Change Division, 2016; Vargas, 2018). Carbon stored by trees accumulates over the years, and therefore our urban street trees will increase their storage of carbon with time as long as we keep them healthy (Nowak et al., n.d.).

Based on Olympia's average annual urban forestry program costs (2014-2019) tree and stump removal accounts for approximately 25% of the annual budget ($120,000) as seen in Appendix B. Additionally, tree removal activities result in the emission of greenhouse gases as a result of the tools and equipment used by tree crews (Mcpherson et al., 1997). Therefore, keeping the street trees maintained and healthy would provide the environmental and social service by trees to store carbon, and the economic benefit of reducing tree removal costs for the City of Olympia.

Of all the greenhouse gases associated with climate change emitted each year, carbon dioxide is emitted in the largest quantity as a by-product of human activities (Epa & Change Division, 2016). In 2016, emissions in the Olympia area reached approximately 750,000 U.S. short tons of carbon dioxide (TRPC, 2018). Street tree carbon sequestration is an important ecosystem service when considering the global issue of climate change and the adverse climate stressors on local urban environments like Olympia, leading to increased summer temperatures and poor air quality (Nowak et al., n.d.; TRPC, 2017). Trees absorb atmospheric carbon dioxide through small openings on their leaves called stomata as they grow new leaves and woody biomass (Kuehler, Hathaway, & Tirpak, 2017). Using iTree Streets I determined that each year Olympia's street trees sequester **420,000 pounds** of atmospheric carbon dioxide. This demonstrates that trees are active participants in the carbon cycle and should be considered as a tactic for regional climate mitigation (Glaeser & Kahn, 2010; Nowak et al., n.d.)

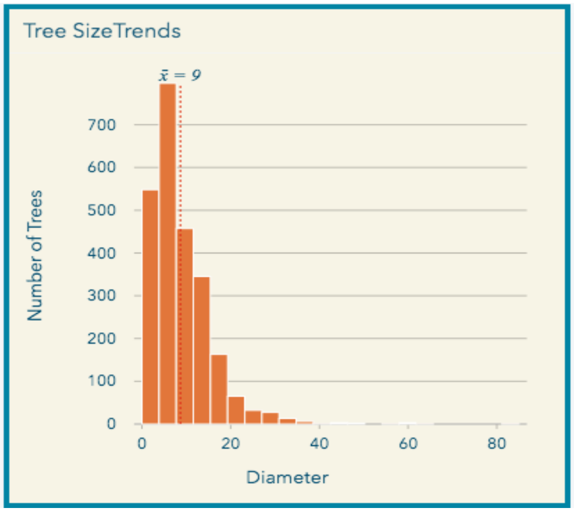
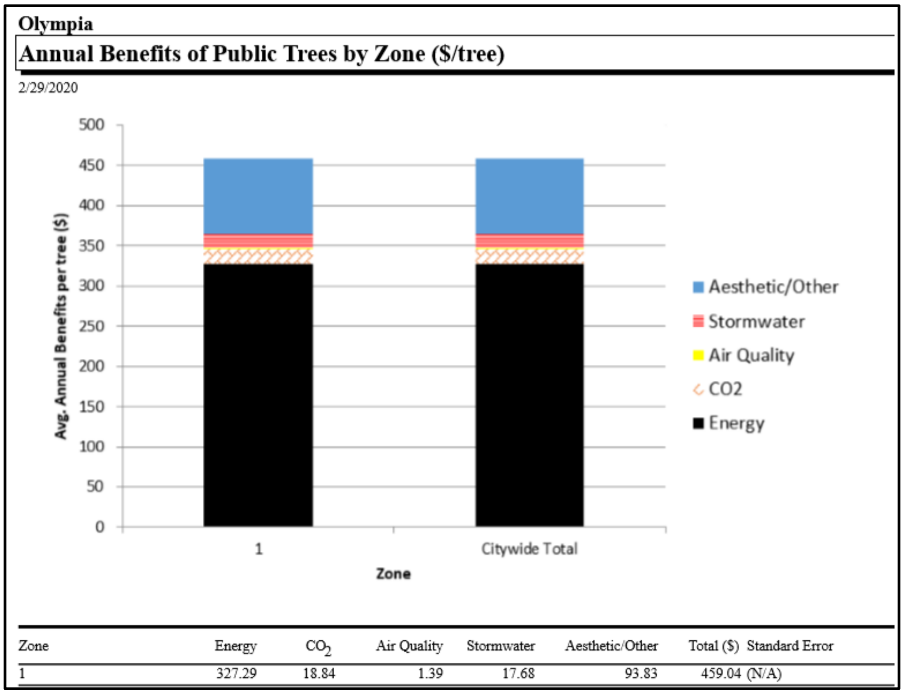


Figure 22. ArcGIS Insights results for growspace trends.

Olympia's street tree population composition warrants a closer look when discussing the sequestration of carbon. The actual rate of carbon sequestration will vary with species, but in general, younger and faster growing trees have higher annual sequestration rates (US DOE EIA, 1998). As we can see in Figure 22**,** the average DBH of Olympia's street trees is 9 inches, with 46.5% of the population smaller than 6 inches DBH. This younger, still maturing street tree population may have an increased carbon sequestration rate as a consequence. I recommend further research on this is topic to refine the annual sequestration estimates for Olympia's street trees.

Street trees also help to mitigate carbon dioxide (CO2) emissions by regulating ambient temperature and thus reducing energy use in nearby buildings, thereby reducing energy demands from local energy providers, such as Puget Sound Energy for Olympia. In this study I determined that this ecosystem service has resulted in a decrease of **150,000 pounds** of carbon emissions from power plants due from reduced energy use, with an associated annual net savings of approximately **$45,000,** incorporating Social Cost of Carbon values (Epa & Change Division, 2016; Vargas, 2018). Note that these results do account for CO2 released as trees die and decompose and CO2 released during the care and maintenance of trees. In total, I determined in this study that Olympia street trees sequester and mitigate **530,000 pounds** or **265 tons** of atmospheric carbon dioxide each year.

Street trees and energy reduction



Olympia

Annual Benefits of Public Trees by Zone ($/tree)

2/29/2020

Zone	Energy	CO_2	Air Quality	Stormwater	Aesthetic/Other	Total ($)	Standard Error
1	327.29	18.84	1.39	17.68	93.83	459.04	(N/A)

Figure 23. iTree Streets graph results from iTree Streets showing the total amount of ecosystem services provided by each street tree in an average year. Note that the Olympia inventory was not broken down into zones, Zone 1 is the same as the Citywide Total.

For the past 50 years the primary sources of CO2 emissions for the City of Olympia have been from energy supply, industry, and deforestation (Olympia & Lacey, 2010). Now however, the top two leading sources of emissions in Olympia are from buildings and vehicles (City of Olympia, 2016). As we can see in the bar graph of the iTree Streets report (Figure 23), the estimated energy benefits and avoided emissions from the presence of nearby trees to buildings are one of the most important economic contributions of Olympia's street trees (shown in black). The energy and emissions savings arise from the cooling benefits of trees during summer months and the wind-chill reduction benefits in winter months (Manning, 2008). According to iTree Streets results, Olympia's street trees reduce building energy demands citywide at an associated cost of more than **$785,000 each year**. On average, that's an annual energy savings benefit of **$330 per tree** for nearby homes and businesses.

When looking at the landscape in GIS, we can use a Heat Index method of detecting surface heat from aerial imagery to determine the relationship of trees to the temperature of their surroundings (Figure 24). The cooler colors of green to blue show the areas that have cooler temperature responses, and the warmer colors of orange to red represent higher temperature responses from surfaces. In these images we can see how the image on the top has more tree cover and a more general cooler response, while the bottom image shows a predominance of warm surfaces, with street trees circles in black in each image. We can determine that the trees in the downtown image on the right are in a prime position to be performing these important services of reducing urban temperatures, reducing A/C unit emissions, and thereby improving air quality in dense urban environments.

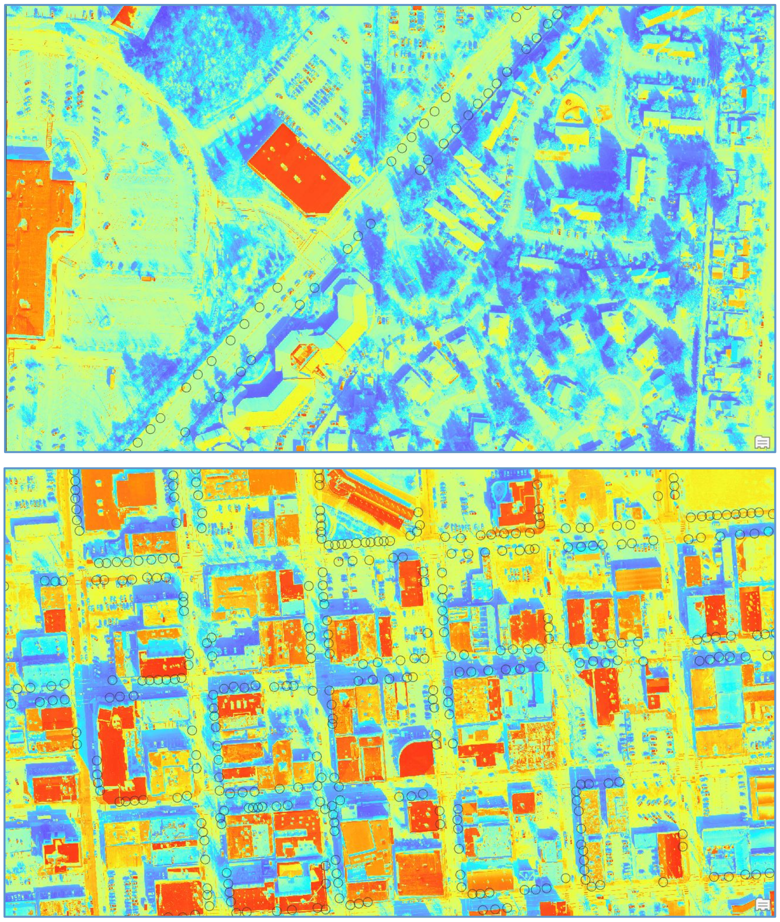


Figure 24. Heat Index GIS maps of Westside Olympia (top) and Downtown Olympia (bottom) showing the relationship of trees (circled in black) and the cooling effect they have on the landscape, thereby reducing building energy demands.

Because of the predominantly urban nature of the region analyzed (especially accounting for the roughly 680 trees in the downtown region) the potential energy benefits from trees and the associated mitigation of emissions could be considerable, as reflected by the average energy-saving values calculated by iTree Streets and as illustrated Heat Index map. Because of missing tree measurements required for energy analysis in iTree Eco, the energy benefit results from iTree Streets were used in this study, and reflect estimated energy benefits across the whole city. Therefore, a geospatial analysis of trees was of particular importance in order to illustrate the potential benefits of the street trees under study on building emissions and avoided emissions from energy production by Puget Sound Energy.

The map detail of Downtown Olympia (Figure 25) includes tree locations (shown as green points), impervious surfaces (shown in grey), and buildings (shown in orange). The blue halos around each green point show the 60-foot radius around each tree location.

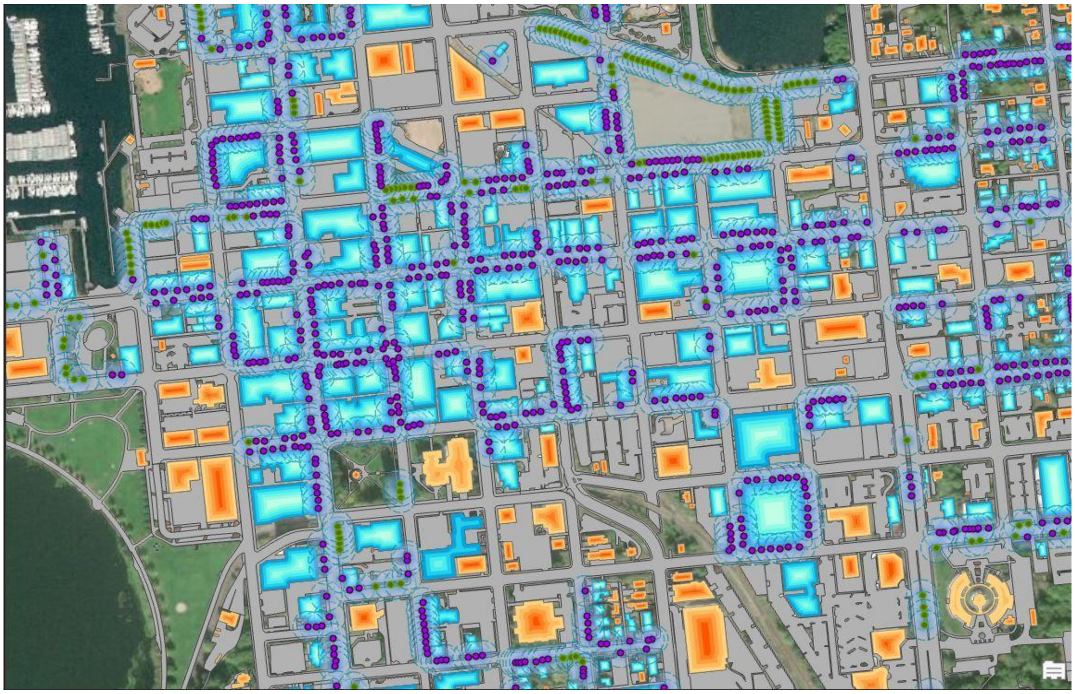


Figure 25. All trees within 60-feet of buildings are here colored purple, and all trees 60-feet from a tree are colored blue. Visual assessment of tree energy benefits to buildings may be possible from this GIS method of analysis.

Figure 25 depicts this snapshot of the downtown area and highlights the number of street trees providing energy savings (purple points) to businesses and apartments (highlighted in blue). Out of the entire living street tree population (2,334), 73% of Olympia's street trees (1,692) are within 60 feet of a building— the range for providing some form of energy benefits for 673 buildings and homes.

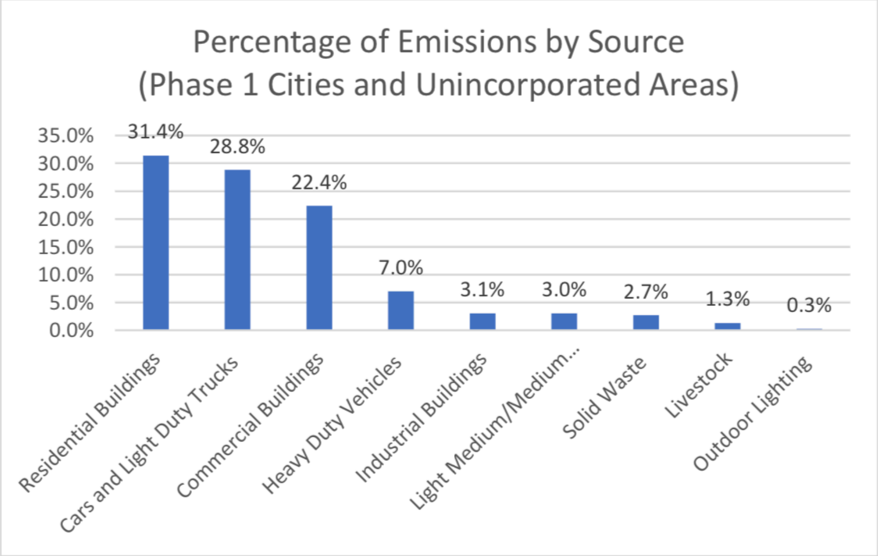


Figure 26. All trees within 60-feet of buildings are here colored purple, and all trees 60-feet from a tree are colored blue. Visual assessment of tree energy benefits to buildings may be possible from this GIS method of analysis.

Although green energy and building efficiency tactics are being employed to address building emissions, these research results are exciting when considering the Thurston County Action Team (TCAT) report showing commercial and residential buildings as the primary contributors to greenhouse gas emissions in the county (Figure 26). The TCAT Climate Mitigation Plan also set an emission reduction target of 45% by 2030, a portion of which must come from those very buildings. Further research needs to be done to improve these energy reducing ecosystem service estimates however, as the tree height and canopy size affect the amount of shade they provide, and the distance and cardinal direction to nearby buildings are important factors to take into account to best determine the energy benefits.

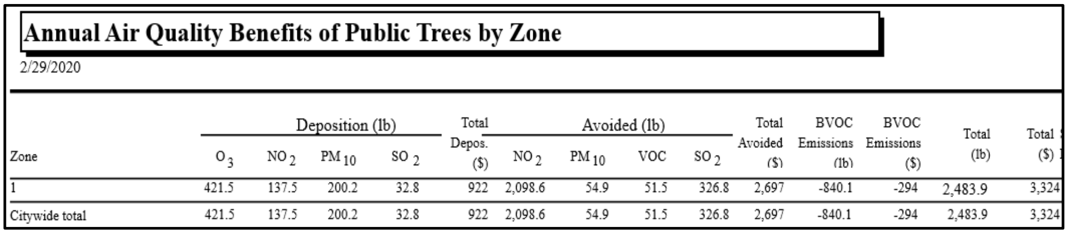
Street trees and air quality

Healthy leaf area links directly to many of the benefits of trees, including shade and absorption of airborne pollutants (Grote et al., 2016). As Glanzberg states, "all exchanges occur across boundaries, [therefore] the more surface area, the more exchange is possible" (Glanzberg, 2020). According to iTree Eco, Olympia street trees canopy covers approximately 75.1 acres of leaf area across the urban landscape. Using GIS we can visualize the range of canopy cooling benefits across the city as seen in Figure 27 The blue areas in this snapshot depict the 60-foot range of cooling benefits provided by the street tree population along the major travel corridors and downtown Olympia (Forest Service, 2020).

Figure 27. Tree energy range in blue across the City of Olympia, showing the range of cooling, and air quality services provided by street trees.

Based on the air pollution models of iTree Streets, I calculated Olympia's street tree population intercepts and prevents almost **2,500 pounds** of airborne pollutants every year, including nitrogen dioxide, sulfur dioxide, ozone, and particulate matter of 10 microns (PM2.5) (Table 11). Sulfur dioxide (SO2) is a byproduct of fuel combustion in vehicles and energy production (Grote et al., 2016). According to iTree Streets, street trees intercept (through deposition) **33 pounds of sulfur dioxide** from vehicle emissions, and provide a secondary benefit of reducing the energy demands of nearby buildings thereby avoiding the emissions of **327 pounds of sulfur dioxide** from the process of energy production by Puget Sound Energy. If we consider that vehicles are a major source of sulfur dioxide emissions and are the second leading source of greenhouse gas emissions in Thurston County (Figure 26) street trees in Olympia could play a role in mitigating air pollution and carbon dioxide at the source of emissions.

Table 11. iTree Streets results for annual air quality shown in total pounds of deposition (pollutants intercepted by the trees), total pounds avoided (energy emissions reduced thereby reducing air pollutants), and total biogenic volatile compound (BVOC) emissions (natural emissions from trees) here shown as a negative value.

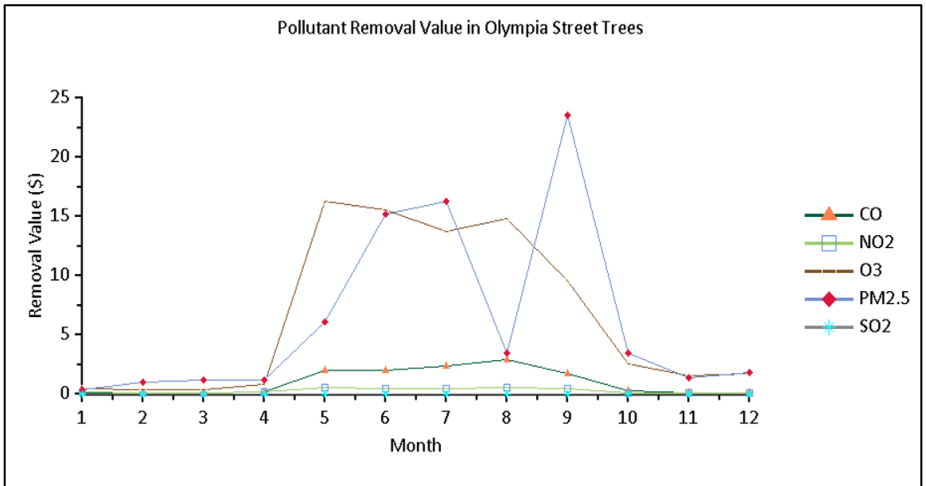


Annual Air Quality Benefits of Public Trees by Zone

2/29/2020

	Deposition (lb)				Total Depos.	Avoided (lb)				Total Avoided	BVOC Emissions	BVOC Emissions	Total	Total
Zone	O_3	NO_2	PM_{10}	SO_2	($)	NO_2	PM_{10}	VOC	SO_2	($)	(lb)	($)	(lb)	($)
1	421.5	137.5	200.2	32.8	922	2,098.6	54.9	51.5	326.8	2,697	-840.1	-294	2,483.9	3,324
Citywide total	421.5	137.5	200.2	32.8	922	2,098.6	54.9	51.5	326.8	2,697	-840.1	-294	2,483.9	3,324

As stated previously, city residents are exposed to an average of 200 different types of air pollutants in a day (Sicard et al., 2018). Using the air pollution models of iTree Streets, I determined that Olympia's street trees intercept **794 pounds of air pollutants** annually, including **200 pounds of particulate matter** (PM10) which have been linked to increased rates of asthma (Epa & of Air, 2014). This socio-economic benefit of the trees is further illustrated in the graph shown in Figure 28, which tracks the air-pollution interception trends over the course of an average year in Olympia.



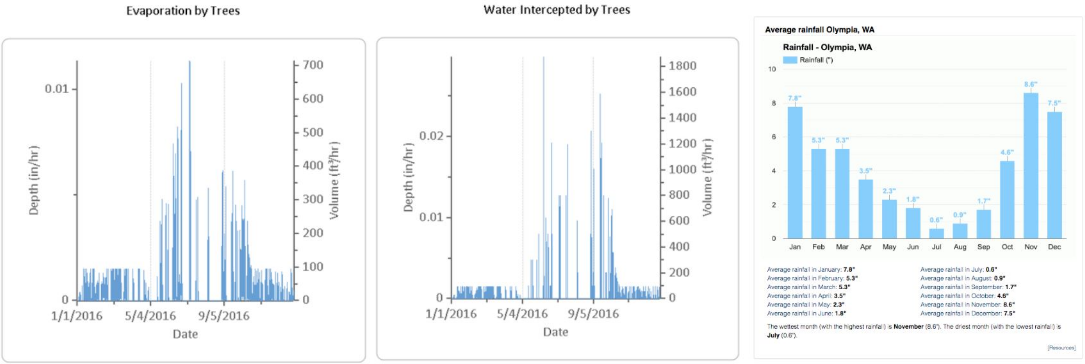
Pollution removal value is calculated based on the prices of $0.66 per pound (CO), $0.21 per pound (O3), $0.03 per pound (NO2), $0.01 per pound (SO2), $13.17 per pound (PM2.5).
A value of zero may indicate that ancillary data (pollution, weather, energy, etc.) is not available for this location or that the reported amounts are too small to be shown.

Figure 28. iTree Eco results for monthly pollutant removal trends by Olympia's street trees.

iTree Eco results for air quality (Figure 28) includes the rate of carbon dioxide, nitrogen dioxide, ozone, particulate matter 2.5, and sulfur dioxide interception by Olympia's street trees. Although the exact numbers in the iTree Eco results cannot be considered reliable, the behavior trends illustrated in this graph are a worthy inclusion in this discussion. Because deciduous trees make up the bulk of Olympia's street trees, the amount of air pollution that they intercept drops off as they lose their leaves each autumn, increasing again as they put on fresh growth in the spring (Figure 28). On average, trees growing in Thurston County experience 280 leaf-off days, and 127 leaf-on days (Weather Atlas, n.d.). This pattern of change in leaf canopy can also help to explain some differences in other ecosystem services, such as their role in intercepting seasonal rainfall.

Street trees and stormwater

iTree Eco results depend on crown health variables to determine the amount of precipitation intercepted by leaves; therefore, the volume of intercepted rainfall results, and their relative dollar amounts are inconclusive. However, these results can illustrate trends in tree behavior based on local weather data and leaf-off seasonality, explained below.



Average rainfall in January: **7.8"**
Average rainfall in February: **5.3"**
Average rainfall in March: **5.3"**
Average rainfall in April: **3.5"**
Average rainfall in May: **2.3"**
Average rainfall in June: **1.8"**
Average rainfall in July: **0.6"**
Average rainfall in August: **0.9"**
Average rainfall in September: **1.7"**
Average rainfall in October: **4.6"**
Average rainfall in November: **8.6"**
Average rainfall in December: **7.5"**

The wettest month (with the highest rainfall) is **November** (8.6"). The driest month (with the lowest rainfall) is **July** (0.6").

Figure 29. iTree Eco result of water interception and evaporation provided by trees each month for the weather data year of 2016, showing a dramatic rise in stormwater benefits in leaf-on seasons.

The iTree Eco result (Figure 29) displays the monthly evaporation provided by street trees in inches per hour and cubic feet per hour, illustrating the vast increase of evaporation during warmer months which helps to cool the urban landscape (Berland et al., 2017). As shown in Figure 29, the trend of stormwater interception is fairly low in leaf-off seasons and increases dramatically during leaf-on seasons. This could be explained by the dominance of deciduous tree species in the Olympia street tree population, and by the Mediterranean climate of the Northwest—wet winters and arid summers. However, the stormwater interception potential during the leaf-on season could still be substantial as seen in the summer months shown in Figure 29. According to the local weather station data, the total average rainfall is 15.4" for the leaf-on months (April-October), which is equal to approximately 6 billion gallons of rainfall during leaf-on months in Olympia ("Weather Atlas," n.d.).

This stormwater service has a secondary benefit of reducing the flow of pollutants into receiving bodies of water. The Stormwater Management Plan of 2019 and new state discharge permit requirements mandate that the City of Olympia reduce stormwater flows and the discharge of pollutants to protect regional water quality. The stormwater services of street trees support the efforts of the City of Olympia to reduce the volume of stormwater runoff by more than **1.5 million gallons of stormwater over the year**. Economically speaking, with stormwater costs valued at $0.0277 per gallon (based on 2016 weather data and City of Olympia utility costs) this provides a savings to Olympia's stormwater department of approximately **$42,500 annually**.

Figure 30. NDVI analysis using aerial imagery of Downtown Olympia in winter, showing red chloryphil response of grass and conifer trees, but no response from street trees (circled in black).

These stormwater results suggest that the predominantly deciduous tree population of our street trees provides less in terms of stormwater services during the rainy-season in Olympia. Based on studies in the Pacific Northwest, a conifer intercepts and transpires an estimated 30% of the precipitation that falls on it, while a deciduous tree intercepts and transpires 15% (Clapp, Ryan, Harper, & Bloniarz, 2014; Illgen, 2011). Based on the NDVI maps (Figure 30) showing the canopy of evergreen and deciduous trees during the winter leaf-off season, there is a chlorophyll response from conifer trees on private property and green spaces throughout the city during winter months, showing that the conifer canopy cover actively intercepts stormwater year-round. Considering conifer species only make up 0.5% of the street tree population, these stormwater results in this study should be considered preliminary research and recommendations for further study are included at the close of this chapter.

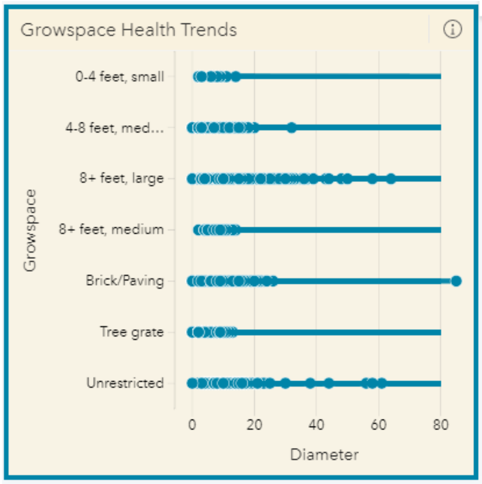


Figure 31. ArcGIS Insights results for DBH trends showing the location and sizes of the street trees.

Finally, rainfall infiltration into the soil and uptake by tree roots may be important to consider in urban settings that have planted predominantly deciduous trees. It is widely recognized in the literature that larger healthier trees provide greater ecosystem benefits including stormwater interception and infiltration abilities; therefore, the logic follows that we should consider surface types, local annual rainfall patterns, tree health, and the growspace size of our deciduous urban trees to understand the potential for stormwater soil infiltration (Mcpherson, Nowak, & Rowntree, 1994). As seen in Figure 30, 4’x4’planter spaces (0-4 feet small, tree grate, brick/paving) show street trees with a smaller DBH sizes on average than 8+ feet large and unrestricted growspaces. This suggests that larger growspaces for Olympia’s street trees would facilitate tree growth and long-term tree health.

Limitations and recommendations

The inventory of street trees used in this research represents a relatively small population of trees within Olympia and does not capture the ecosystem services provided by the entire urban forest within the City of Olympia. Based on the limitations of this inventory I recommend that an urban tree canopy cover assessment be completed for the entire City of Olympia boundary. A complete assessment would determine the percentage of total canopy cover, and evergreen and deciduous makeup of our urban forest, providing a more comprehensive calculation of stormwater and other ecosystem services provided by our urban forest. I also recommend that conservation of conifer tree species within our city boundaries be supported in our city's tree policies, and preferential planting of conifer species should be given when suitable open grow spaces are available to support year-round stormwater processing benefits within city limits to reduce water pollution and stormwater volume.

iTree software limitations exist as well. iTree Streets results rely on models used to determine average annual tree benefits from the 2002 study of the City of Longview Washington (Gregory et al., 2002). Although my research methods included current regional utility rates and regional city information, results from this study should serve as a preliminary study of the potential ecosystem benefits of Olympia's street trees and guideline for an improved method of ecosystem-benefits analysis. The iTree Eco results serve to show the importance of collecting tree variables during routine street tree maintenance that can improve the data needed for future analysis using the superior ecosystem benefit models embedded in the iTree Eco software.

Based on the limitations I encountered using the existing tree inventory in this study, I further recommend that the street tree inventory include additional tree measurements so that the iTree Eco models could be run with the street tree inventory data. This would enable future ecosystem service research, including the important energy benefits of our street trees using superior models of calculation included in iTree Eco or similar urban forestry software. I recommend to the urban forestry department that the following variables be added to their inventory for future study and planning:

1. Tree health condition as a percentage (0-100%).
2. Crown condition as a percentage (0-100%).

3. Percent of crown missing.
4. Top and bottom crown height in feet.
5. Location of tree to structure (North, South, East, West).
6. Distance in feet to nearest structure to determine energy benefits.

Additionally, the inventory used in this study included the qualitative measurement of the tree's condition (Good-Poor) that proved ill suited for the quantitative parameters required for canopy and tree health by iTree Streets and iTree Eco. Currently, the condition assessment of the street trees in the inventory by maintenance crews "in practice... turn out to be fairly arbitrary" (B. Moulton, pers. comm. Feb. 13, 2020). Therefore I recommend that the "iTree Eco Tree Assessment Guide" or similar tree health guide be followed by tree maintenance staff in order to establish a baseline and standard of tree health ratings.

Lastly, this research included ecosystem services and the relative monetary values for air quality, stormwater, carbon, and energy, and did not include other equally important benefits of trees such as the psychological benefits, community enhancement, crime reduction, and property value increase benefits of urban trees. Further research on the benefits of our urban forest is recommended. Most importantly, I recommend that urban forest strategies for enhancing the ecosystem services provided by street trees be adopted by the Olympia urban forestry department (Hastie, 2003). For example, by supplying generous water to trees seasonally, tree health and canopy fullness increases, improving ecosystem service yields such as air pollution removal (Nowak, 2000), and evaporation during summer months to cool the surrounding urban landscape (Berland et al., 2017).

With the study limitations and recommendations for future research in mind, these results highlight the possibility of improved future urban forest valuation assessments for Olympia and other cities, to further advocate for the conservation and care of our urban tree. As seen from the multiple results from the iTree programs and GIS geospatial analyses in this section, the many services of trees can be quantified and understood in greater detail using urban forestry software and existing tree inventory data. Furthermore, these results illustrate the social, environmental, and economic benefits of a healthy urban forest, and how these benefits can support our local climate mitigation goals.

CONCLUSION

Nature's economy shall be the base for our own, for it is immutable, but ours is secondary. An economist without knowledge of nature is therefore like a physicist without knowledge of mathematics.

—Carl Linnaeus (as translated by Lisbet Koerner)

In this study I was able to determine the annual ecosystem services of Olympia's street trees using iTree urban forestry software and GIS mapping software. Using these valuation methods can provide a deeper understanding of urban trees, and the benefits of the complex living network of trees within the city environment. We have seen in this study that Olympia street trees support the long-term health of our residents by improving our local air-quality by removing 2,500 pounds of air pollutants, reduce asthma-related medical costs by $45,000, and improve water quality by processing 1.5 million gallons of stormwater each year.

Throughout this study we have also seen how urban trees can contribute to our goals of urban sustainability and climate mitigation. Using the iTree methods of valuation I determined that our street trees sequester 420,000 pounds of atmospheric carbon dioxide each year, and reduce citywide energy spending by $785,000 annually. As part of the cost-benefit analysis of Olympia's street tree program I was found that the multitude of ecosystem services provided by our street trees outweigh the costs associated with tree planting and maintenance. Annually, these ecosystem services culminate in an annual net *benefit* of more than $600,000 for the City of Olympia and its residents, with an associated average annual benefit value of $450 per tree. Essentially, for every $1 spent annually by the City on street trees, $2.30 in ecosystem benefits are provided by street trees in return.

The results of this study may be for a relatively small population of trees within the City of Olympia, but it underscores the important role of trees in the long-term health and resilience of our local communities and the natural environment. The collective ecosystem services of our urban forest deserve to be included in our climate mitigation plans; further research needs to aid our urban forestry departments in their efforts to maintain our trees for the health and well being of residents and the environment.

In fact, this research has shown that the street trees within Olympia help to reduce carbon emissions, improve local air quality, intercept stormwater, and reduce energy demands, but as a final thought, let us imagine the City of Olympia as seen from above. Imagine the entire urban forest that stretches across the 20 square miles of the city landscape, and the magnitude of services they are silently performing. Pull back then even farther and imagine the tree canopy that stretches across the 774 square miles of Thurston County. As we continue to grow our cities and develop our climate mitigation plans we should do so holistically and with awareness of the ways our trees support that goal of sustainable development. By recognizing and valuing the ecosystem services of trees we can better advocate for the conservation and health of our urban forests. These natural processes are happening all around us, cleaning our air and improving our water— all we have to do is look.

Planning, building, and implementing a comprehensive climate mitigation plan is founded on the principle that we are responsible for the present and future health of each other and the environment; we seek a sustainable way to grow and exist in a world with finite resources. Sustainable development of our cities and surrounding environments must include a methodical approach to the economic management of our natural resources, including our urban forests (Hastie, 2003; Munasinghe, 1993). If "value" is defined as the belief that something is held to deserve; the importance, worth, or usefulness of something, how then do we as a society, or a city, value our urban forest?

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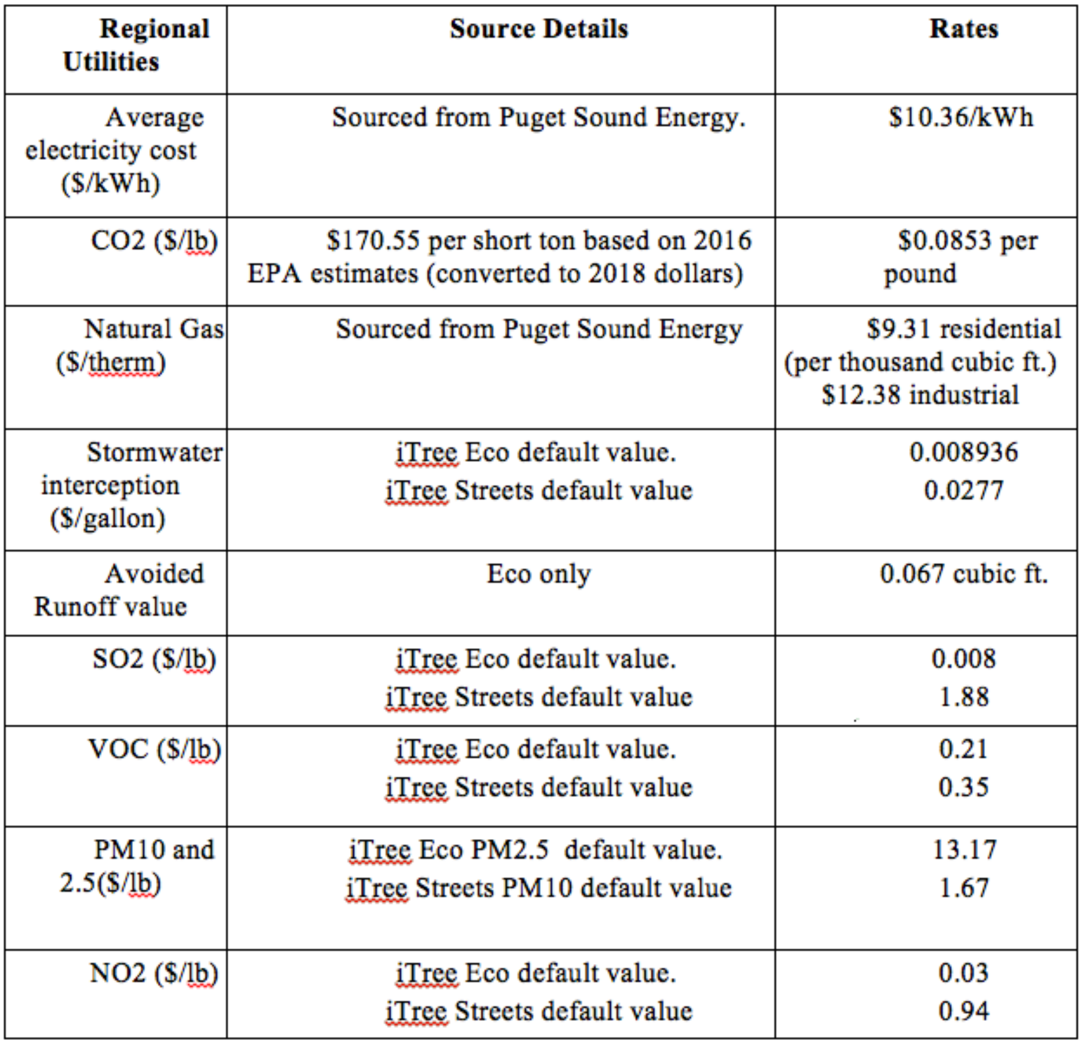
APPENDIX A. EMISSION RATES

Appendix A1. Research methods for acquiring rates.

Tree Mitigation Benefit Rates



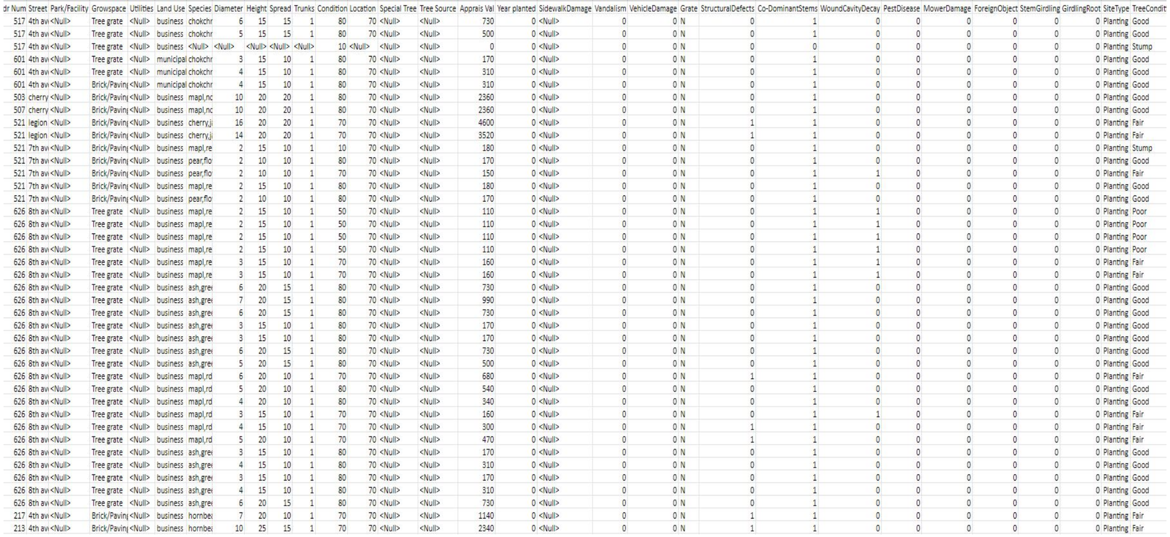
Regional Utilities	Source Details	Rates
Average electricity cost ($/kWh)	Sourced from Puget Sound Energy.	$10.36/kWh
CO2 ($/lb)	$170.55 per short ton based on 2016 EPA estimates (converted to 2018 dollars)	$0.0853 per pound
Natural Gas ($/therm)	Sourced from Puget Sound Energy	$9.31 residential (per thousand cubic ft.) $12.38 industrial
Stormwater interception ($/gallon)	iTree Eco default value. iTree Streets default value	0.008936 0.0277
Avoided Runoff value	Eco only	0.067 cubic ft.
SO2 ($/lb)	iTree Eco default value. iTree Streets default value	0.008 1.88
VOC ($/lb)	iTree Eco default value. iTree Streets default value	0.21 0.35
PM10 and 2.5($/lb)	iTree Eco PM2.5 default value. iTree Streets PM10 default value	13.17 1.67
NO2 ($/lb)	iTree Eco default value. iTree Streets default value	0.03 0.94

Appendix A2. Olympia City Data

Population (2019)	51,609
Total land area (sq.miles)	20.09 square miles
Average sidewalk width	6.9 feet
Total linear miles of streets	19,024,260
Average street width	31’
Median home resale value (2019)	$354,494.00

APPENDIX B. REGIONAL DATA

Appendix B1. Olympia Tree Inventory



dr Num	Street	Park/Facility	Growspace	Utilities	Land Use	Species	Diameter	Height	Spread	Trunks	Condition	Location	Special Tree	Tree Source	Apprais Val	Year planted	SidewalkDamage	Vandalism	VehicleDamage	Grate	StructuralDefects	Co-DominantStems	WoundCavityDecay	PestDisease	MowerDamage	ForeignObject	StemGirdling	GirdlingRoot	SiteType	TreeCondit
517	4th av	<Null>	Tree grate	<Null>	business	chokchr	6	15	15	1	80	70	<Null>	<Null>	730	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
517	4th av	<Null>	Tree grate	<Null>	business	chokchr	5	15	15	1	80	70	<Null>	<Null>	500	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
517	4th av	<Null>	Tree grate	<Null>	business	<Null>	<Null>	<Null>	<Null>	<Null>	10	<Null>	<Null>	<Null>	0	0	<Null>	0	0	N	0	0	0	0	0	0	0	0	Planting	Stump
601	4th av	<Null>	Tree grate	<Null>	municipal	chokchr	3	15	10	1	80	70	<Null>	<Null>	170	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
601	4th av	<Null>	Tree grate	<Null>	municipal	chokchr	4	15	10	1	80	70	<Null>	<Null>	310	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
601	4th av	<Null>	Brick/Paving	<Null>	municipal	chokchr	4	15	10	1	80	70	<Null>	<Null>	310	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
503	cherry	<Null>	Brick/Paving	<Null>	business	mapl,nc	10	20	20	1	80	70	<Null>	<Null>	2360	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
507	cherry	<Null>	Brick/Paving	<Null>	business	mapl,nc	10	20	20	1	80	70	<Null>	<Null>	2360	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
521	legion	<Null>	Brick/Paving	<Null>	business	cherry,j	16	20	20	1	70	70	<Null>	<Null>	4600	0	<Null>	0	0	N	1	1	0	0	0	0	0	0	Planting	Fair
521	legion	<Null>	Brick/Paving	<Null>	business	cherry,j	14	20	20	1	70	70	<Null>	<Null>	3520	0	<Null>	0	0	N	1	1	0	0	0	0	0	0	Planting	Fair
521	7th av	<Null>	Brick/Paving	<Null>	business	mapl,re	2	15	10	1	10	70	<Null>	<Null>	180	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Stump
521	7th av	<Null>	Brick/Paving	<Null>	business	pear,flo	2	10	10	1	80	70	<Null>	<Null>	170	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
521	7th av	<Null>	Brick/Paving	<Null>	business	pear,flo	2	10	10	1	70	70	<Null>	<Null>	150	0	<Null>	0	0	N	0	1	1	0	0	0	0	0	Planting	Fair
521	7th av	<Null>	Brick/Paving	<Null>	business	mapl,re	2	15	10	1	80	70	<Null>	<Null>	180	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
521	7th av	<Null>	Brick/Paving	<Null>	business	pear,flo	2	10	10	1	80	70	<Null>	<Null>	170	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
626	8th av	<Null>	Tree grate	<Null>	business	mapl,re	2	15	10	1	50	70	<Null>	<Null>	110	0	<Null>	0	0	N	0	1	1	0	0	0	0	0	Planting	Poor
626	8th av	<Null>	Tree grate	<Null>	business	mapl,re	2	15	10	1	50	70	<Null>	<Null>	110	0	<Null>	0	0	N	0	1	1	0	0	0	0	0	Planting	Poor
626	8th av	<Null>	Tree grate	<Null>	business	mapl,re	2	15	10	1	50	70	<Null>	<Null>	110	0	<Null>	0	0	N	0	1	1	0	0	0	0	0	Planting	Poor
626	8th av	<Null>	Tree grate	<Null>	business	mapl,re	2	15	10	1	50	70	<Null>	<Null>	110	0	<Null>	0	0	N	0	1	1	0	0	0	0	0	Planting	Poor
626	8th av	<Null>	Tree grate	<Null>	business	mapl,re	3	15	10	1	70	70	<Null>	<Null>	160	0	<Null>	0	0	N	0	1	1	0	0	0	0	0	Planting	Fair
626	8th av	<Null>	Tree grate	<Null>	business	mapl,re	3	15	10	1	70	70	<Null>	<Null>	160	0	<Null>	0	0	N	0	1	1	0	0	0	0	0	Planting	Fair
626	8th av	<Null>	Tree grate	<Null>	business	ash,gre	6	20	15	1	80	70	<Null>	<Null>	730	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
626	8th av	<Null>	Tree grate	<Null>	business	ash,gre	7	20	15	1	80	70	<Null>	<Null>	990	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
626	8th av	<Null>	Tree grate	<Null>	business	ash,gre	6	20	15	1	80	70	<Null>	<Null>	730	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
626	8th av	<Null>	Tree grate	<Null>	business	ash,gre	3	15	10	1	80	70	<Null>	<Null>	170	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
626	8th av	<Null>	Tree grate	<Null>	business	ash,gre	3	15	10	1	80	70	<Null>	<Null>	170	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
626	8th av	<Null>	Tree grate	<Null>	business	ash,gre	6	20	15	1	80	70	<Null>	<Null>	730	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
626	8th av	<Null>	Tree grate	<Null>	business	ash,gre	5	20	15	1	80	70	<Null>	<Null>	500	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
626	8th av	<Null>	Tree grate	<Null>	business	mapl,rd	6	20	10	1	70	70	<Null>	<Null>	680	0	<Null>	0	0	N	1	1	0	0	0	0	0	0	Planting	Fair
626	8th av	<Null>	Tree grate	<Null>	business	mapl,rd	5	20	10	1	80	70	<Null>	<Null>	540	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
626	8th av	<Null>	Tree grate	<Null>	business	mapl,rd	4	20	10	1	80	70	<Null>	<Null>	340	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
626	8th av	<Null>	Tree grate	<Null>	business	mapl,rd	3	15	10	1	70	70	<Null>	<Null>	160	0	<Null>	0	0	N	0	1	1	0	0	0	0	0	Planting	Fair
626	8th av	<Null>	Tree grate	<Null>	business	mapl,rd	4	15	10	1	70	70	<Null>	<Null>	300	0	<Null>	0	0	N	1	1	0	0	0	0	0	0	Planting	Fair
626	8th av	<Null>	Tree grate	<Null>	business	mapl,rd	5	20	10	1	70	70	<Null>	<Null>	470	0	<Null>	0	0	N	1	1	0	0	0	0	0	0	Planting	Fair
626	8th av	<Null>	Tree grate	<Null>	business	ash,gre	3	15	10	1	80	70	<Null>	<Null>	170	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
626	8th av	<Null>	Tree grate	<Null>	business	ash,gre	4	15	10	1	80	70	<Null>	<Null>	310	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
626	8th av	<Null>	Tree grate	<Null>	business	ash,gre	3	15	10	1	80	70	<Null>	<Null>	170	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
626	8th av	<Null>	Tree grate	<Null>	business	ash,gre	4	15	10	1	80	70	<Null>	<Null>	310	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
626	8th av	<Null>	Tree grate	<Null>	business	ash,gre	6	20	15	1	80	70	<Null>	<Null>	730	0	<Null>	0	0	N	0	1	0	0	0	0	0	0	Planting	Good
217	4th av	<Null>	Brick/Paving	<Null>	business	hornbea	7	20	10	1	70	70	<Null>	<Null>	1140	0	<Null>	0	0	N	1	1	0	0	0	0	0	0	Planting	Fair
213	4th av	<Null>	Brick/Paving	<Null>	business	hornbea	10	25	15	1	70	70	<Null>	<Null>	2340	0	<Null>	0	0	N	1	1	0	0	0	0	0	0	Planting	Fair

Appendix B2. Olympia City sidewalk and street design standards

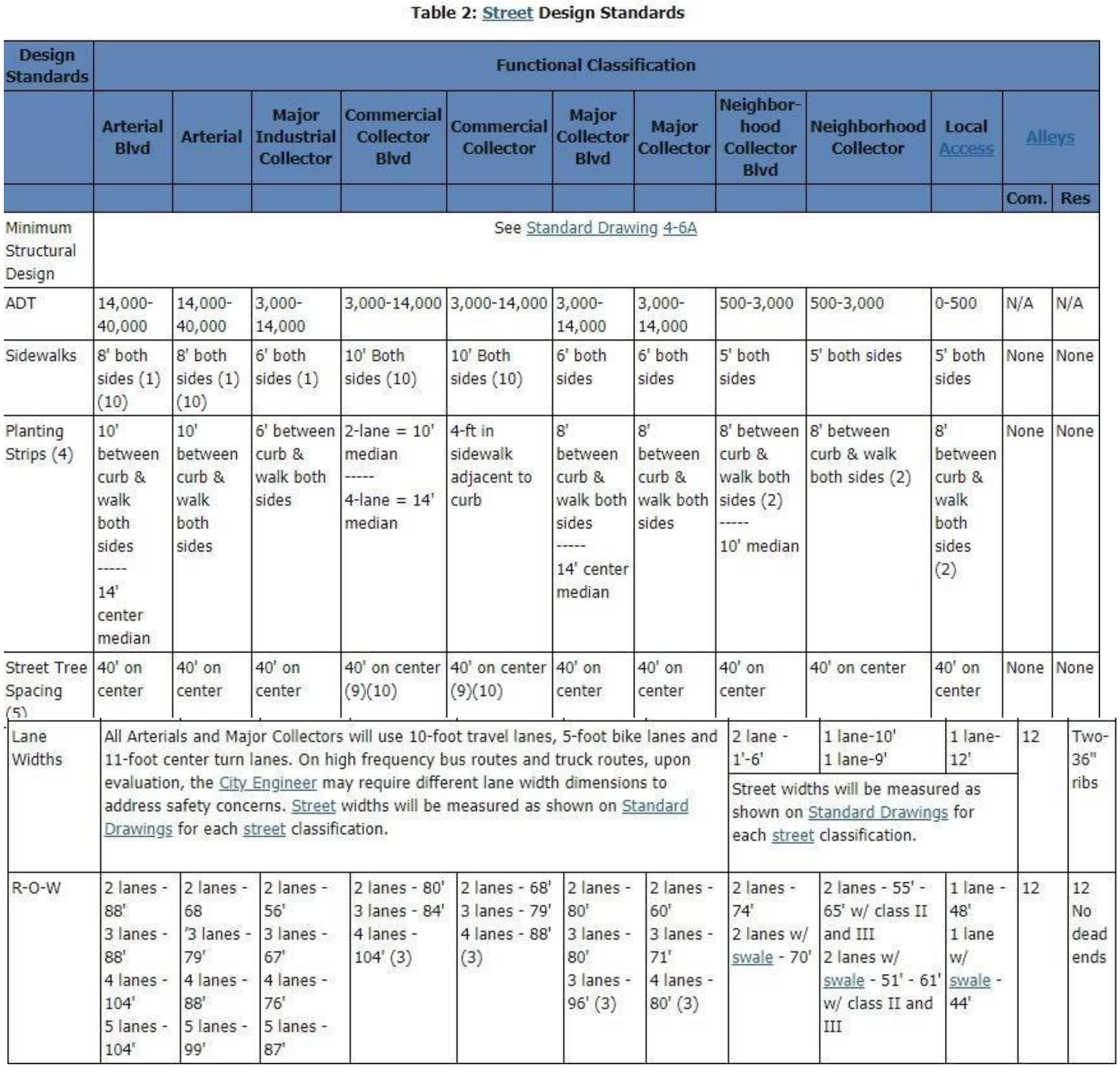


Table 2: Street Design Standards

Design Standards	Functional Classification											
	Arterial Blvd	Arterial	Major Industrial Collector	Commercial Collector Blvd	Commercial Collector	Major Collector Blvd	Major Collector	Neighbor-hood Collector Blvd	Neighborhood Collector	Local Access	Alleys	
											Com.	Res
Minimum Structural Design	See Standard Drawing 4-6A											
ADT	14,000-40,000	14,000-40,000	3,000-14,000	3,000-14,000	3,000-14,000	3,000-14,000	3,000-14,000	500-3,000	500-3,000	0-500	N/A	N/A
Sidewalks	8' both sides (1) (10)	8' both sides (1) (10)	6' both sides (1)	10' Both sides (10)	10' Both sides (10)	6' both sides	6' both sides	5' both sides	5' both sides	5' both sides	None	None
Planting Strips (4)	10' between curb & walk both sides ----- 14' center median	10' between curb & walk both sides	6' between curb & walk both sides	2-lane = 10' median ----- 4-lane = 14' median	4-ft in sidewalk adjacent to curb	8' between curb & walk both sides ----- 14' center median	8' between curb & walk both sides	8' between curb & walk both sides (2) ----- 10' median	8' between curb & walk both sides (2)	8' between curb & walk both sides (2)	None	None
Street Tree Spacing (5)	40' on center	40' on center	40' on center	40' on center (9)(10)	40' on center (9)(10)	40' on center	40' on center	40' on center	40' on center	40' on center	None	None
Lane Widths	All Arterials and Major Collectors will use 10-foot travel lanes, 5-foot bike lanes and 11-foot center turn lanes. On high frequency bus routes and truck routes, upon evaluation, the City Engineer may require different lane width dimensions to address safety concerns. Street widths will be measured as shown on Standard Drawings for each street classification.							2 lane - 1'-6' Street widths will be measured as shown on Standard Drawings for each street classification.	1 lane-10' 1 lane-9'	1 lane-12'	12	Two-36" ribs
R-O-W	2 lanes - 88' 3 lanes - 88' 4 lanes - 104' 5 lanes - 104'	2 lanes - 68 '3 lanes - 79' 4 lanes - 88' 5 lanes - 99'	2 lanes - 56' 3 lanes - 67' 4 lanes - 76' 5 lanes - 87'	2 lanes - 80' 3 lanes - 84' 4 lanes - 104' (3)	2 lanes - 68' 3 lanes - 79' 4 lanes - 88' (3)	2 lanes - 80' 3 lanes - 80' 3 lanes - 96' (3)	2 lanes - 60' 3 lanes - 71' 4 lanes - 80' (3)	2 lanes - 74' 2 lanes w/ swale - 70'	2 lanes - 55' - 65' w/ class II and III 2 lanes w/ swale - 51' - 61' w/ class II and III	1 lane - 48' 1 lane w/ swale - 44'	12	12 No dead ends

Appendix B3. Annual itemized list of expenses by Olympia's Urban Forestry program.*

Program Expenses	**2014-2019 Average**
Planting costs**	$28,407
Maintenance/pruning costs	$76,402
Watering costs	$3,500
Tree and stump removal costs	$119,610
Litter/Storm clean-up costs	$9,180
Annual inspection/answer service requests	$22,790
Infrastructure repair due to trees	$60,186
Program administration costs	$165,648

*Annual costs rounded to the nearest dollar during import into software.

**Planting moratorium in effect since 2016. Planting efforts have steadily declined since 2015.

APPENDIX C. ITREE METHODS

Appendix C1. Land use data entered into iTree programs

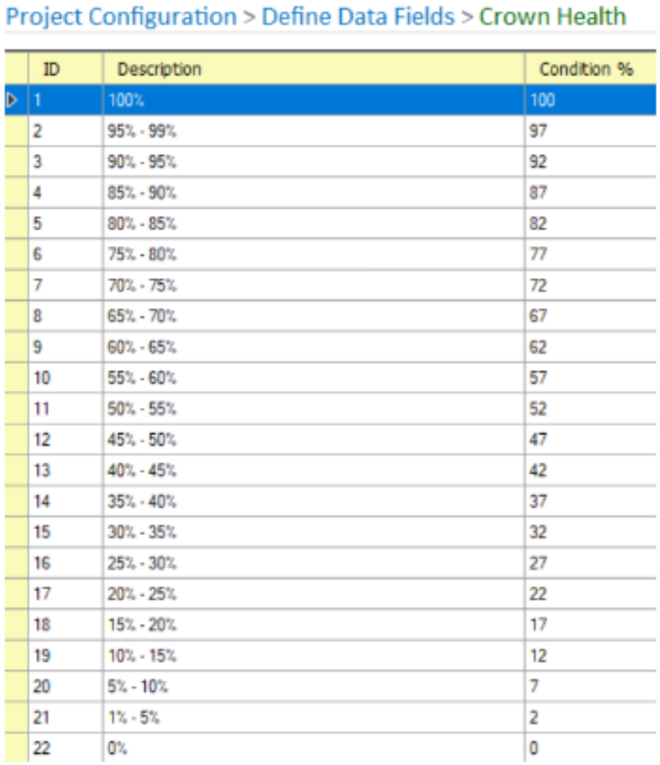
Code	Land use category	Code	Planter Type
1	Single family/private residential	1	Tree grate
2	Multi-family residential	2	Brick/paving
3	Small commercial/business/church/school	3	0-4 feet, small
4	Industrial/large commercial/municipal	4	4-8 feet, medium
5	Median/street planting/island	5	8+ feet, medium
6	Park tree	6	8+ feet, large
7	Park/vacant/parking lot	7	Unrestricted

Appendix C2. Tree measurement variables and descriptions entered into iTree programs.

Tree Variables	**Details**
DBH	Diameter breast height of tree (in inches)
Condition	Health of the overall trees, including canopy health, for future management recommendations (coded values e.g. 70=fair 80=good)
Land use	General land use type surrounding the tree location (e.g. commercial or industrial)
Site type	Planting types such as a cutout or planting strip
Tree height	Height measured to the top of the crown in feet
Sidewalk damage	Represented in inches of sidewalk lift, e.g. 1" lift. Coded values 1: 0-¾ in. 2: ¾-1½ in. 3: >1 ½ in
Pest detection	Coded values (1=yes, 2=no)

Appendix C3. Eco Canopy Health Classes

Eco Health Default Classes:



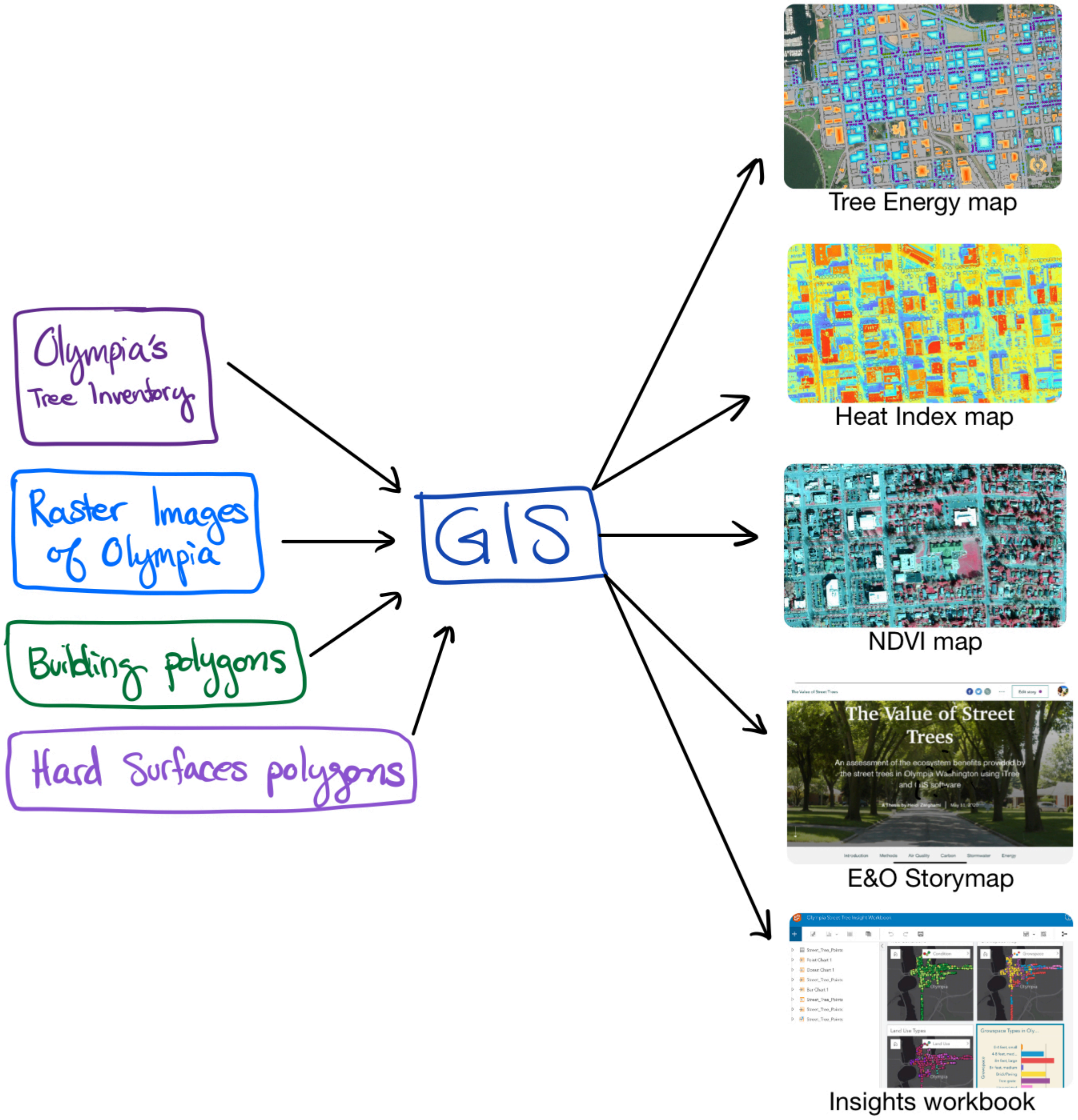
Project Configuration > Define Data Fields > Crown Health

ID	Description	Condition %
1	100%	100
2	95% - 99%	97
3	90% - 95%	92
4	85% - 90%	87
5	80% - 85%	82
6	75% - 80%	77
7	70% - 75%	72
8	65% - 70%	67
9	60% - 65%	62
10	55% - 60%	57
11	50% - 55%	52
12	45% - 50%	47
13	40% - 45%	42
14	35% - 40%	37
15	30% - 35%	32
16	25% - 30%	27
17	20% - 25%	22
18	15% - 20%	17
19	10% - 15%	12
20	5% - 10%	7
21	1% - 5%	2
22	0%	0

Entered Olympia inventory crown condition percentages as relative to Eco default values.

Code 1: Excellent = N/A
Code 5: Good = 82
Code 7: Fair = 72
Code 11: Poor = 52
Code 15: V. Poor = 32
Code 22: Stump = 0
Code 22: Vacant = 0

APPENDIX D. ARCGIS WORKFLOW



APPENDIX E. ITREE RESULTS COMPARISON

iTree Streets and iTree Eco results comparison

REPORTS	Streets	Eco	Notes
Total trees imported	2,399.00	2,346.00	
Total Trees analyzed	2,399.00	2,253.00	93 tree entries show NULL benefit values
Air Quality pollutant (lbs.)	2,483.90	525.90	missing canopy data in ECO
Air Quality pollutant value	$3,324.00	$168.00	missing canopy data in ECO
Aesthetic Values	$225,106.00	n/a	missing canopy data in ECO
Natural Gas avoided gigajoules	272.30	n/a	missing canopy data in ECO
Natural Gas avoided $	$24,024.00	n/a	missing canopy data in ECO
Electricity saved gigajoules	264.50	n/a	missing canopy data in ECO
Electricity saved $	$761,154.00	n/a	missing canopy data in ECO
Energy saved	73.5 MWh	n/a	missing canopy data in ECO
Total Energy $ saved	$785,178.00	n/a	missing canopy data in ECO
CO2 mitigated (lbs.)	148,321.00	n/a	missing canopy data in ECO
CO2 mitigated $	$12,652.00	n/a	missing canopy data in ECO
CO2 (lbs.)	529,966.00	4,610,000.00	Eco CO2 equivalent
CO2 Net Benefits	$45,206.00	n/a	missing canopy data in ECO
Carbon Sequestered (tons)	210.16	12.65	
Carbon Sequestration $	$35,852.00	$2,156.67	
Carbon Storage (tons)	2,511.66	628.40	
Carbon Storage $	$428,489.00	$107,181.12	
Total rainfall interception (gal.)	1,531,141.00	235,345.90	Eco: Conservative model for avoided runoff
Total rainfall interception $	$42,416.00	$6,519.07	Eco: Conservative model for avoided runoff
Evapotranspiration ft cubed/yr	n/a	745,039.00	STREETS calculates interception in gal. only
Evaporation ft cubed/yr	n/a	152,034.70	STREETS calculates interception in gal. only
Water intercepted ft cubed/yr	n/a	153,069.00	STREETS calculates interception in gal. only
Oxygen (tons)	n/a	33.72	Not generated in STREETS
Total Benefits	$1,101,231.00	$4,427.69	
Total Structural/Appraisal $	$6,360,262.00	$4,080,000.00	
Oxygen produced per/yr	n/a	33.72 tons	Oxygen reports n/a in STREETS