Estimating Carbon Sequestration of Green Roofs and Elevated Green Courtyards in Seattle

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Abstract

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As carbon dioxide (CO_2) becomes increasingly concentrated in the atmosphere and rapidly accelerates climate change, efforts should be put forth not just to reduce CO_2 emissions but to also remove CO_2 from the atmosphere. Vegetation naturally absorbs CO_2 from the surrounding atmosphere through the process of photosynthesis. Thus, increasing the amount of vegetation is a method to remove more CO_2 from the air. Meanwhile, as cities continue developing while often seeking more greenspace for human and urban ecological functions, roofs of urban buildings take up vast amounts of space and go largely unused. Adding greenspace on roofs and other elevated portions of buildings can provide a plethora of functions including absorbing, or sequestering, CO_2. Research on the CO_2 sequestration of green roofs is a relatively new but expanding field which provides promise for significant amounts of CO_2 sequestration if green roofs are widespread. General interest in Seattle's green roofs has also grown over the past 10 - 15 years, and policy has been put forth to encourage their implementation. Efforts have also been put forth to map, quantify, and categorize existing green roofs. However, these efforts are far from complete. Seattle, which has been experiencing rapid building and development over many years, with likely continuation into the future, has potential for more green roofs and additional CO_2 sequestration. The question driving this research is: How much carbon is annually sequestered by Seattle's green roofs and elevated green courtyards?

This thesis provides an up-to-date mapping of much of Seattle's rooftop vegetation. On the basis of this data, available green roof carbon sequestration experiments are analyzed, and their sequestration rates collected and categorized into green roofs and elevated green courtyards of differing vegetation size, or intensity. The city is explored with aerial/satellite/building-level/street-level imagery, and building vegetation is recorded on a map. Areas not mapped are estimated for vegetative content. Carbon sequestration amount is estimated based on amount of green roof and elevated courtyard vegetation with a basis of previous research on rooftop sequestration rates. In total, 2,669,267 sq. ft. of green roofs and elevated green courtyards, or 0.096 sq. miles, are measured and estimated across Seattle. The estimated annual sequestration of these green roofs and elevated green courtyards is 2,151,079 kg CO_2 per year, or 2,151 metric tons of CO_2 per year. These results are discussed, limitations are described, and suggestions are made for future research. Ultimately, more direct carbon sequestration and mapping measurements in Seattle could ensure a more locally-accurate set of sequestration rates and green roof/elevated green courtyard quantifications. In creating an up-to-date map for much of the city and estimations for the rest, and creating Seattle's first carbon sequestration estimation for these vegetated urban features, it is hoped that a strong foundation has been built to continue refining sequestration estimates in Seattle and to elucidate the potential for additional carbon sequestration in Seattle and beyond.

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Acknowledgements

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Chapter 1: Introduction

1.1: Motivation for Thesis

As climate change becomes an increasingly urgent issue, strategies to reduce its progression and impacts are becoming increasingly important for ecological systems, including human and urban ecosystems. This thesis addresses one such strategy in Seattle: the potential for green roofs to reduce carbon dioxide, a central factor impacting climate change.

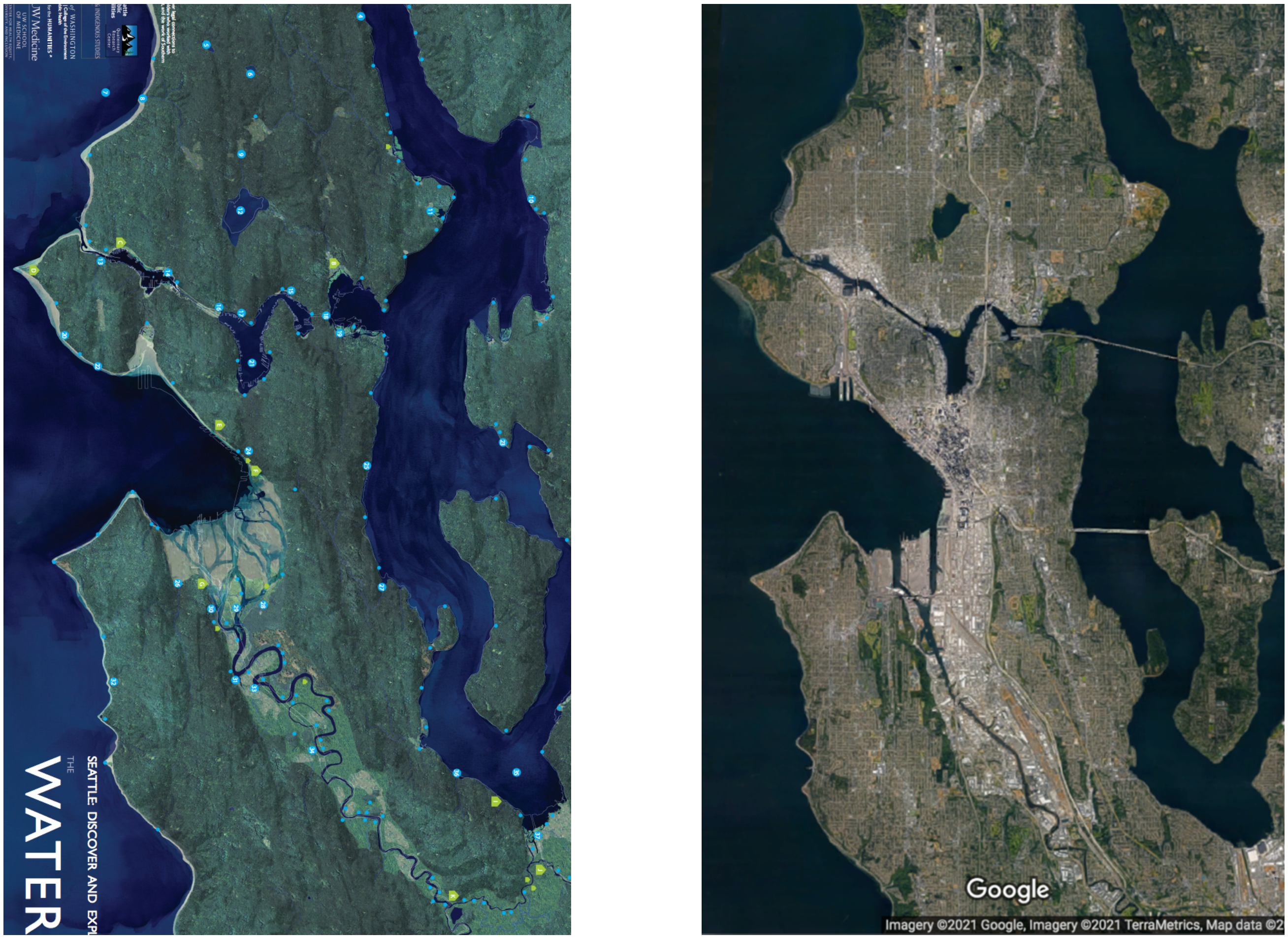
Though the Earth's climate has always been changing, sometimes significantly, the rate and degree of change occurring presently is unprecedented (Cui, Schubert, & Jahren, 2020). Climate change is tightly linked to increasing global temperature, and increasing global temperature is tightly linked to the increasing concentration of greenhouse gases in the atmosphere (Global Monitoring Laboratory, n.d.; Lüthi et al., 2008; Smith & Smith, 2015). Greenhouse gases in the atmosphere are directly responsible for the Earth's greenhouse effect, which is a means of trapping heat within the atmosphere, thereby warming the Earth (Smith & Smith, 2015; Ussiri & Lal, 2017). In proper balance, greenhouse gases provide sufficient warmth to the Earth during the day, and that heat is released at night. However, numerous human activities in the past 200 years have led to historically extreme increases in atmospheric greenhouse gases, disrupting the previous balance and leading to global warming (Ussiri & Lal, 2017). Carbon dioxide is arguably the most important greenhouse gas, responsible for ~72% of the human-driven increase in the greenhouse effect (Houghton, 2009). Carbon dioxide is more highly concentrated in the atmosphere today than at any point in at least the last 800,000 years (Lüthi et al, 2008). There are two fundamental methods of addressing the issue of excessive atmospheric carbon dioxide in order to limit global warming and climate change. One method is to reduce the sources which emit carbon dioxide into the atmosphere, and the other method is to remove carbon dioxide which is in the atmosphere. This thesis will discuss both, but will focus primarily on the latter method as the goal is to understand how much carbon dioxide can be sequestered (i.e., removed) by green roofs in the city of Seattle.

The primary reasons for increased carbon dioxide in the atmosphere over the past 200 years are land use changes (e.g., deforestation, agricultural techniques) and burning of fossil fuels; land use changes were initially the predominant cause of increased atmospheric carbon dioxide, but as industrialization expanded, fossil fuel burning became the leading cause of carbon dioxide emissions (Ussiri & Lal, 2017). Regarding land use changes, an important consideration is that, in addition to the aforementioned changes leading to emissions, they also reduce the natural environments' ability to sequester carbon (the mechanisms of carbon sequestration will be detailed later; Ussiri & Lal, 2017). As demonstrated in Figure 1, the natural landscape of Seattle has changed dramatically in recent times (Google, 2021; Lewis & Monez, 2019).

While much could be said about the urban form on the right in relation to carbon dioxide emissions, it is also clear that much of the original forest is gone, along with much of the carbon sequestration capacity of the area. With the vast amount of space now taken up by buildings, and only a tiny fraction of those buildings having vegetation on them, it raises a question of how much and what types of vegetation could be placed on buildings in Seattle such that some of the original carbon sequestration capacity can be restored. To establish a basis for estimation, it is important to have an understanding of the existing vegetation on buildings and how much carbon this vegetation may be sequestering.

Figure 1

Seattle Before Establishment as a City (Left) and Seattle Today (Right)



Note. Map on left designed by Lewis & Monez, 2019 as part of larger project by Sheikh et al., 2019 and the Burke Museum. Image on left from *The Waterlines Project*, by Sheikh et al., 2019, (https://www.burkemuseum.org/static/waterlines/project_map.html). In public domain/Reprinted with permission from the Burke Museum. Map on right by Google Maps, 2021, (https://www.google.com/maps/@47.6133438,-122.3093785,30808m/data=!3m1!1e3). Copyright by Google, 2021.

This can create a foundation upon which to consider altering current building vegetation policies and designs such as green roofs, which in some way can replace the carbon sequestration and other ecosystem services formerly provided by historical patterns of vegetation growth.

There have been efforts to quantify, categorize, and map green roofs and similar elevated building vegetation in Seattle, but these efforts are out-of-date, lacking in comprehensiveness, and/or lacking in accuracy (Stenning, 2008; McIntosh, 2010; Matza, 2018; Steinberg, 2018; Sobolt, n.d./2019). This thesis is an effort to advance the breadth and the depth of this urban-environmental data in a way that emphasizes both accurate accounting and an appreciation of the larger picture, all while bringing the records more up-to-date.

Furthermore, this is the first work to analyze Seattle's green roofs in terms of carbon sequestration. McIntosh (2010), Matza (2018), and Steinberg (2018) briefly mentioned or discussed this benefit of green roofs (Getter et al., 2009; Whittinghill et al., 2014). However, carbon sequestration was not a central focus in those studies of Seattle green roofs. This is the central motivation for this thesis, organized to answer this question: Currently, how much carbon is annually sequestered by Seattle's green roofs and elevated green courtyards?

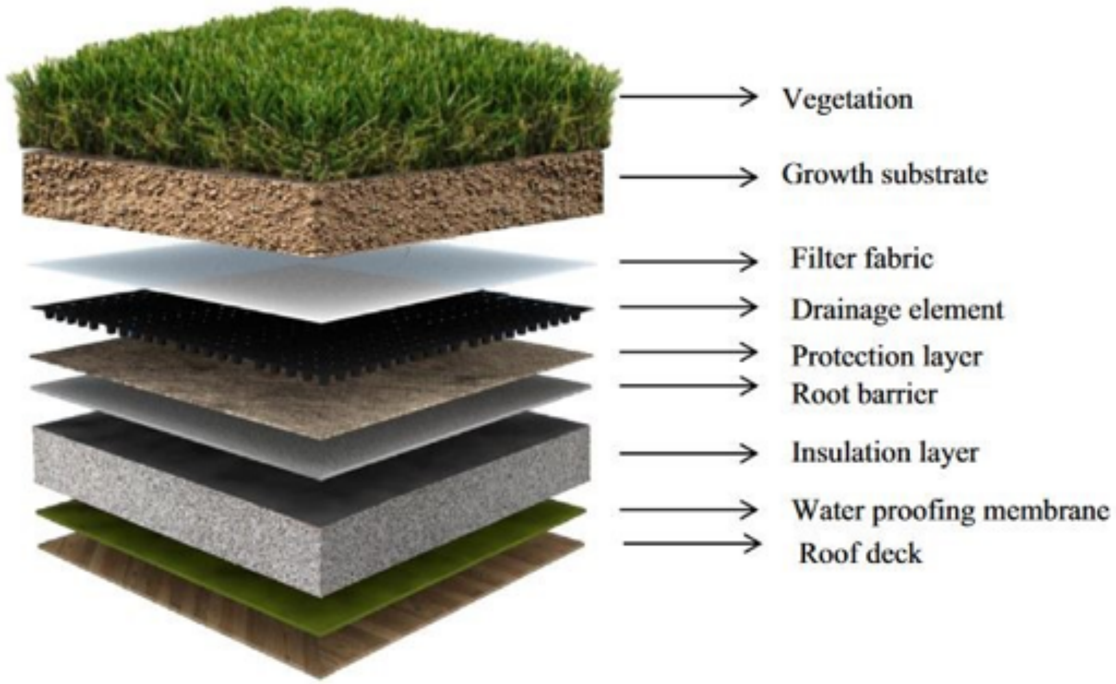
To answer this question, it is important to first have a clear understanding of green roofs and visualize this often under-examined feature of the built environment.

1.2: An Introduction to Green Roofs

Green roofs, simply, are vegetative structures on top of buildings. Modern green roofs are not solely vegetation but a set of layers which support the vegetation and soil above as well as the building roof below. Figure 2 shows a typical set of green roof layers. Below the vegetation and growth substrate are layers which execute functions like allowing excess water to drain from the soil, a filter to prevent soil clogging the water drainage layer, protecting the roof from plant roots or any water that made its way through the other layers (Pérez & Coma, 2018).

Figure 2

Typical Layers of a Green Roof

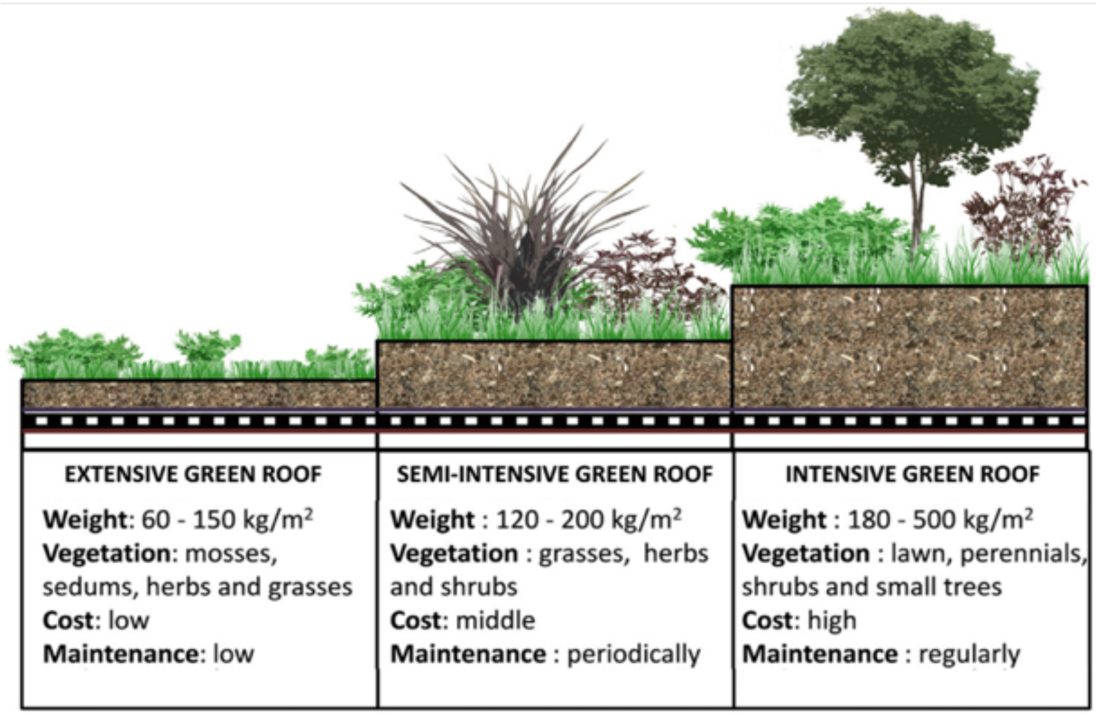


Note. From “Green roofs: A critical review on the role of components, benefits, limitations and trends,” by K. Vijayaraghavan, 2016, *Renewable and Sustainable Energy Reviews, 57,* p. 744. (http://dx.doi.org/10.1016/j.rser.2015.12.119). Copyright 2015 by Elsevier Ltd.

There are different kinds of roofs based on their soil depth, vegetation types, and related structural differences. These are typically classified into three main forms: extensive, semi-intensive, and intensive green roofs. They are shown and described in general terms in Figure 3. Vegetation types and soil depth are particularly important features of green roofs as it relates to carbon sequestration.

Figure 3

*Visualizations and Descriptions of Extensive, Semi-Intensive, and Intensive Green Roof Typologies***.**



EXTENSIVE GREEN ROOF	SEMI-INTENSIVE GREEN ROOF	INTENSIVE GREEN ROOF
Weight: 60 - 150 kg/m^2 **Vegetation**: mosses, sedums, herbs and grasses **Cost**: low **Maintenance**: low	**Weight** : 120 - 200 kg/m^2 **Vegetation** : grasses, herbs and shrubs **Cost**: middle **Maintenance** : periodically	**Weight** : 180 - 500 kg/m^2 **Vegetation** : lawn, perennials, shrubs and small trees **Cost**: high **Maintenance** : regularly

Note. From "Green roof systems: A study of public attitudes and preferences in southern Spain," by R. Fernandez-Cañero, T. Emilsson, C. Fernandez-Barba, & M-Á-H Machuca, 2013, *Journal of Environmental Management, 128,* p. 108. (http://dx.doi.org/10.1016/j.jenvman.2013.04.052). Copyright 2013 by Elsevier Ltd.

Figures 4, 5 and 6 are examples of extensive, semi-intensive, and intensive green roofs, respectively:

Figure 4

An Extensive Green Roof

Note. From *Scandinavian Green Roof Inst*., by International Sustainable Solutions, 2004, Flickr (https://www.flickr.com/photos/46329363@N02/4255371678). CC BY-NC 2.0.

Figure 5

A Semi-Intensive Green Roof

Note. From *comer roof top garden,* by C. Vinz, 2009, Flickr

(https://www.flickr.com/photos/9304424@N02/3657469876). CC BY-NC-ND 2.0.

Figure 6

Intensive Green Roofs

Note. From *trees on roofs near Public Gardens, Boston, 14 June 2012*, by mwms1916, 2012, Flickr (https://www.flickr.com/photos/56874700@N00/7383213372). CC BY-NC-ND 2.0.

While green roofs can be divided into these three classifications, it is common for a given roof to consist of several types of vegetation which vary in size/intensity. Additionally, given the diversity of vegetation and soil depths which exists on rooftops, there is truly a continuum of rooftop vegetation intensity.

It should also be noted that there are a wide variety green roof functions in addition to carbon sequestration that will not be discussed in this thesis (for a review, see Manso et al., 2021).

1.3: Thesis Organization

The rest of the thesis explores carbon sequestration of green roofs in more depth. The first portion of the next chapter elucidates carbon sequestration and its related processes, in addition to what environmental factors can influence it. This is followed by a section which summarizes the research which has been done on green roof carbon sequestration and related topics. Finally, Chapter 2 contains a section describing Seattle-specific efforts to quantify, describe, and map green roofs. Chapter 3 describes the methods formulated to estimate green roof carbon sequestration in Seattle as well as map, categorize, and quantify the green roofs themselves. Chapter 4 details the results of the study. Chapter 5 provides a discussion reflecting on the results and methods in the context of previous research on the topic; limitations and future directions are also discussed. Chapter 6 provides a Conclusion to the thesis. After that are the references used in this study. Finally, the Appendix includes additional details of methods, as well as graphics considered informative for the reader.

Chapter 2: Literature Review

The beginning of this chapter discusses carbon sequestration in terms of basic processes and related factors. Scientific knowledge and research are shared, though the perspective is relatively theoretical in terms of its relationship to green roofs. This background on carbon sequestration is followed by research on its quantification in green roofs. Directly after the green roof carbon sequestration research is a portion on carbon sequestration in trees, as many green roofs contain trees. It is important to note that this literature review finds no existing research directly quantifying rooftop tree carbon sequestration. Finally, analyses are explored that have directly quantified, categorized, and mapped green roofs in Seattle. This is an important foundation for being able to expand upon what is currently known and create what in numerous ways is a more detailed and more comprehensive map of Seattle's green roofs. Additionally, it demonstrates how this thesis moves beyond past work on Seattle's green roofs by estimating their carbon sequestration.

2.1: Theory

2.1.1: Greenhouse Gas Effect and Importance of Carbon Dioxide; Relation to Climate Change

Solar radiation is necessary for all life on Earth; it travels from the sun to this planet and provides light and heat. Some of the solar radiation is absorbed by the Earth's surface. Due to the varied reflectivity of the Earth's surface, some of that solar radiation is reflected directly back into space. Meanwhile, the Earth emits a longer wavelength form of radiation up toward space, but much of that radiation gets trapped by atmospheric gases and gets reflected back toward the Earth. The particular balance of incoming solar radiation, outward-reflected solar radiation, outgoing Earth radiation, atmospheric gases, and inward-reflected Earth radiation has allowed for habitable conditions (Smith & Smith, 2015). However, several of the heat-trapping atmospheric gases, known as the greenhouse gases (GHGs), have been rising significantly in concentration, disrupting this balance and trapping more heat within the Earth's atmosphere, leading to global warming and climate change (IPCC 2007, 2013; Schlesinger and Bernhardt 2013; Ussiri & Lal, 2017).

Among the GHGs that have been rising are carbon dioxide (CO_2), methane, and nitrous oxide (Ussiri & Lal, 2017). Particularly noteworthy is CO_2, the GHG which is responsible for ~72% of the human-driven increase in the greenhouse effect (Houghton, 2009). The significant increase in CO_2 since the Industrial Revolution has been rapid, and the concentration has reached a level that is higher than it has been in at least the last 800,000 years, though some estimates suggest the concentration hasn't been this high in potentially 7 million, 14 million, or even 23 million years (Cui et al., 2020; Lüthi et al, 2008; Zhang et al., 2013). As of late April 2021, the global atmospheric concentration of CO_2 has reached approximately 414.59 parts per million (ppm), compared to 400 ppm in 2015, and 278 ppm in 1750 (Etheridge et al., 1996; Global Monitoring Laboratory, 2021; World Meteorological Organization, 2016).

2.1.2: Plants and Carbon Dioxide Absorption- Basic Mechanism

In order to help stabilize global temperature and climate it is important to reduce atmospheric CO_2. Reducing atmospheric CO_2 is a separate function than reducing CO_2

emissions, which serves the same general mitigation purposes. Even if CO_2 emissions immediately stopped, there would still be an excess of atmospheric CO_2 relative to pre-industrial times. Therefore, actions must be taken to remove, or sequester, CO_2 from the atmosphere. There are two main branches of carbon sequestration: natural/biological and technological. The focus of this thesis is on natural/biological carbon sequestration.

Carbon dioxide is naturally removed from the atmosphere by plants. In order to gain energy and create sugars and ultimately structural components, plants perform the process of photosynthesis. Essentially, photosynthesis is accomplished by plants using the sun's light energy and using carbon dioxide and water to create glucose while producing oxygen. The CO_2 comes from the surrounding air, and the water typically comes from the ground, where it is absorbed up from the soil into the plant roots; it then travels up into the rest of the plant such as the leaves, where photosynthesis usually takes place. Channels in the leaves (called stomata) open up to allow the CO_2 in, while water vapor simultaneously exits the plant through these openings and is released into the surrounding air. There must be enough water in the soil to replenish the plant for it to sustain itself through photosynthesis, and hence continue absorbing CO_2. Part of the typical photosynthetic process is called carboxylation; this is the reaction in the leaf where the CO_2 combines with a 5-carbon molecule (called ribulose bi-phosphate) and becomes two 3-carbon molecules, beginning the integration of the recently-arrived carbon atom into the plant (for a more detailed explanation of photosynthesis, including the molecular mechanisms, see Smith & Smith, 2015).

While plants absorb CO_2 to survive and grow while releasing oxygen, it is also the case that plants use oxygen and release CO_2. This is done through cellular respiration, a process which breaks apart the sugar-like molecules created by photosynthesis in order to get energy for other plant functions. So long as the plant is growing, it absorbs more CO_2 than is released (Smith & Smith, 2015).

2.1.3: Plants and Carbon Dioxide Absorption- Research into Parameters which Influence it

There are many factors which affect the amount of CO_2 absorbed by plants. One factor is simply plant size, as "…larger plants generally have a greater net carbon gain or absolute growth rate (grams per unit time) than do smaller plants…" (Smith & Smith, 2015, p. 448). In terms of environmental conditions, it is generally the case that plentiful sunlight and water, warm but not hot temperatures, nutrients in the soil, adequate airflow, and a supply of CO_2 in the surrounding air increase the rates of CO_2 uptake and photosynthesis. Plants have various adaptations to deal with different and changing conditions, within and between plants (Smith & Smith, 2015).

Within a given plant, an example of a physiological adaptation is the ability to open or close the stomata according to different conditions- if there is a lack of water available to the plant, it closes stomata to prevent water loss, though this then reduces CO_2 uptake (Smith & Smith, 2015). Another example is the flexible allocation of carbon to different parts of the plant under different conditions- when there is a reduction in soil water, plants allocate more carbon to the plant roots in order to maximize water uptake and reduce water loss through creating more leaves; alternatively, with sufficient water, plants allocate more carbon to the leaves which can allow for more water loss and carbon intake for photosynthesis (Austin et al., 2009; Smith & Smith, 2015). Theoretically, this flexibility can be optimized to maximize carbon uptake.

Between plants, there are variations adapted for different conditions. One example is plants being 'shade-intolerant' or 'shade-tolerant.' With adequate sunlight, shade-intolerant plants have higher levels of carbon uptake and photosynthesis than shade-tolerant plants due to the quantity of photosynthetic enzymes they produce. Alternatively, shade-tolerant plants are able to survive in low-light conditions which are untenable for shade-intolerant plants; however, in locations with adequate sunlight, the shade-tolerant plants cannot match the carbon uptake and photosynthetic ability of shade-intolerant plants because the shade-tolerant plants are unable to produce enough photosynthetic enzymes. The ability to survive in a wider variety of circumstances also limits the ability to thrive in certain circumstances (Augspurger, 1982; Gomez-Aparicio et al., 2006; Smith & Smith, 2015).

Different kinds of plants have different kinds of metabolic systems. The most commonly-known type of plants are called C3 plants, which is named for 3-carbon molecules quickly formed from the incoming CO_2 and another molecule. This is also called the Calvin cycle. There are two other main plant metabolic systems: the C4 plants with their C4 pathway, and the crassulacean acid metabolism (CAM) plants with their CAM pathway; these two pathways are different than the ‘standard’ C3 pathway because the C4 and CAM plants exist in hotter and drier environments and need to conserve water. Both C4 and CAM are more efficient with water use in terms of photosynthesis. C4 can potentially have a higher photosynthesis rate than C3 plants, but has higher energy costs, as well. CAM plants exist in even drier and hotter conditions—cacti and jade plants belong in this group (Black & Osmond, 2003; Smith & Smith, 2015). C4 plants conduct photosynthesis in a spatially separated way compared to C3 plants, while CAM plants conduct photosynthesis in a temporally separated way—opening stomata at night and absorbing CO_2 then (Smith & Smith, 2015). C4 plants are generally grasses which are not naturally common in the Pacific Northwest (Teeri & Stone, 1976). CAM plant metabolisms are often not needed in the Pacific Northwest, either, although several species of *Sedum* are options for green roofs in Seattle (City of Seattle, 2010). *Sedum* plants are among the most common green roof plants in a variety of climates, due to their ability to withstand relatively harsh rooftop conditions, in addition to low watering and maintenance needs (see research in Chapter 2.2 below).

The continuing increase in atmospheric carbon dioxide will continue to exacerbate the effects of climate change. However, it is notable that plants have an adaptation to increasing CO_2 levels called the CO_2 fertilization effect. The CO_2 fertilization effect means that plants are able to absorb more CO_2, and so the increasing concentration in the air diffuses into the plants and increases photosynthesis and plant growth (assuming enough water and nutrients). Plants do provide some level of regulatory response by narrowing or reducing their stomata (Smith & Smith, 2015). A meta-analysis summarized the results of studies performing a naturalistic type of experiment which elevates CO_2 levels in open-air environments and examines plants' responses. The meta-analysis found that, in comparison to CO_2 levels averaging 366 ppm, CO_2 levels averaging 567 ppm increased (light-saturated) photosynthesis by an overall mean of 31% for C3 plants. While photosynthesis decreased by ~2% for C4 grasses, photosynthesis increased by ~11% for C4 crops, ~13% for C3 crops, ~37% for C3 grasses, ~21% for shrubs, and ~47% for trees (Ainsworth & Rogers, 2007). Another meta-analysis examined plant biomass growth in elevated CO_2 levels compared to growth at current CO_2 (current at the time of the studies). In examining 280 C3 plant species, 30 C4 plant species, and 6 CAM species, it was found that elevated CO_2 led to an average C3 plant biomass increase of 47%, an average C4 plant biomass increase of 11%, and an average CAM plant biomass increase of 21%. C3 species were subdivided into (1) crops, (2) wild herbaceous plants, and (3) woody plants. Crops' biomass increased by an average of 59%, wild herbaceous plants' biomass increased by an average of

41%, and woody plants' (usually in the form of seedlings) biomass increased by an average of 49% (Poorter & Pérez-Soba, 2002, as cited in Smith & Smith, 2015). In an examination of seven tree species over the course of three to eight years, growth remained greater in all species in elevated CO_2 conditions compared to current (at the time of the studies) CO_2 levels, though some of the species grew at only a slightly higher level after a few years than at current CO_2 levels due to plant adaptations (Poorter & Pérez-Soba, 2002, as cited in Smith & Smith, 2015). Smith & Smith (2015) state that some studies show more carbon going to roots than leaves in elevated CO_2 conditions; this may depend on numerous factors. One general factor in plant growth under elevated CO_2 conditions is limitation of other conditions for plant growth. For example, water and nutrient limitations can limit plant growth under elevated CO_2 conditions; indeed, these limitations may be causing the decreasing CO_2 fertilization effect which has been seen globally between 1982 and 2015 (Wang et al., 2020). It is suggested that nutrient limitations could cause the CO_2 fertilization effect to stop when atmospheric CO_2 reaches 550 - 650 ppm (Körner & Bazzaz, 1996, as cited in Falkowski et al., 2000). Additionally, it must be noted that the CO_2 fertilization effect is not ubiquitous, as demonstrated by mature trees in old-growth forests in British Columbia (Hararuk et al., 2019).

2.1.4: Soil, Nutrient Cycling, Decomposition, Respiration, and CO_2

Critical in the discussion of carbon sequestration and plant life is the area underneath plants—the soil. Soil is the ground, which is made up of many materials and is classified as having several distinct layers. In general, soil at or close to the ground's surface has a large amount of dead organic matter such as leaves and twigs in various states of decomposition.

Living organisms and rocks also exist at the top level. Below the surface is increasingly decomposed dead organic material within a soil with minerals. There is a transition through increasing soil depth toward less organic material and the more minerals. Additionally, the soil becomes rockier as it goes deeper, until there exist mostly rocks and minerals, along with fossilized organic material, and eventually mostly just rock materials (Smith & Smith, 2015). Dead organic material on the ground and in the soil below the surface gets broken down into simpler chemical forms through the process of decomposition, and the process of decomposition in vegetated landscapes includes several organisms such as fungi, bacteria, worms, and millipedes.

The process of decomposition is an essential process to consider regarding both nutrient availability for plants as well as the flow of carbon. When leaves and twigs fall or when plants die, fungi begin to feed on and decompose these materials. Other organisms then continue decomposing those materials, and additional organisms feed on the fungi which fed on the dead plant matter. Over time, and often with the influence of water, the original plant material is broken down/metabolized into inorganic minerals in forms which can be dissolved in water and are often absorbed into plant roots as nutrients for plant growth. Thus, there is a common recycling of nutrients in vegetative ecosystems. Regarding the fungi and the organisms which feed on the fungi, the main element being transferred between them is carbon, which does not get absorbed back into the plants through the soil. Carbon from dead plant matter is often either inside decomposers (or those that feed on decomposers) or is released through these organisms' cellular respiration back to the atmosphere. Small amounts of dead plant matter occasionally do not get fully decomposed, and over geologic time scales, those incompletely-decomposed carbon materials add up to substantial amounts of carbon and eventually end up relatively deep in the

Earth and become fossil fuels (Smith & Smith, 2015). Dead organic matter is not the supplement of carbon for decomposers—plant roots release carbon-rich exudates for microbial-decomposing fungi as well as bacteria. In turn, bacteria have the energy to break down soil/organic matter which has less easily available nutrients. They then ingest these nutrients, such as nitrogen. Then predators ingest the bacteria and release the nitrogen in a form that allows for uptake by plants, ultimately making it worthwhile for the plant to release significant amounts of carbon through its roots. This is part of the larger cycle between carbon gain and carbon loss in plants, and the cycling of carbon between land and the atmosphere (Smith & Smith, 2015).

Decomposition, though necessary for nutrient recycling, is one of the most significant natural causes of CO_2 release into the atmosphere due to the cellular respiration of all the organisms consuming the plant matter and so on. Numerous factors can influence decomposition, such as temperature and moisture. Tropical areas with warm and wet conditions, for example, have very significant rates of decomposition; on the other hand, they have very significant rates of carbon sequestration (Smith & Smith, 2015).

Decomposition of organic matter, aside from root exudates, comes from dead plant matter. Thus, aside from leaves or twigs dropping, decomposition occurs on a relatively slow time scale for a green roof system: years or decades if the plants are perennial and do not die back in the winter (a time when decomposition may be lower anyway due to cooler temperatures). The plant breakdown would mostly be when the plants die (assuming the plants are decomposed and not storing the carbon in long-term materials like wood for buildings). Thus, organic nutrients (those not supplied by dust carried into the soil by rain) would be in relatively short supply. Providing organic fertilizer would entail decomposition and cellular respiration due to microbial breakdowns, while inorganic fertilizer would be ready for plant root uptake without decomposition, though it must be used carefully due to other factors (Smith & Smith, 2015). An important consideration for carbon sequestration of green roofs would be a comparison of CO_2 release to the atmosphere from decomposition/cellular respiration vs. CO_2 to the atmosphere from the embodied emissions of inorganic fertilizer production, transportation, etc.

2.1.5: Carbon Cycle

Overall, carbon dioxide is sequestered by plants for use in plant structures. There is cellular respiration by living plants, which releases some CO_2 back to the atmosphere. More carbon is absorbed by a healthy plant than is released. When leaves fall or plants die, the carbon is broken down and absorbed into the food chain, while all of the organisms in the food chain release CO_2 through cellular respiration, either by themselves or by their own predators. Plants, taking in carbon, are ultimately the source of carbon for all organisms thereafter (not counting aquatic carbon cycling). Plants are essentially the only terrestrial organisms removing CO_2 from the atmosphere. Carbon goes throw a flow of biomass, but much of the CO_2 goes back into the air. Globally, under ‘natural’ conditions, the flow of carbon is close to equilibrium, though ultimately various conditions can cause Earth’s land to become either a global source of carbon or a global sink of carbon (Prentice, 2001, as cited in Ussiri & Lal, 2017; Schaphoff et al., 2006).

Regarding the net carbon gain or loss of carbon to the atmosphere from green roof vegetation, it seems that in order to increase natural sequestration (i.e., ensure that this vegetation is a net carbon sink) there would have to be a continual increase in rooftop vegetation over time. In other words, for a green roof to perform as a carbon sink, overall vegetative growth must outweigh natural decay and decomposition of plants so that those processes do not essentially balance out the carbon uptake over time (aside from carbon retained in other biomass). Additionally, lifecycle carbon emissions of green roof systems should be analyzed in order to ensure that the emissions involved in setting them up do not outweigh their sequestration (Shafique et al., 2020).

2.1.6: Climate and Vegetation in the Pacific Northwest and Seattle Area

The climate of a region can impact carbon sequestration by impacting such features as vegetation, soil, and amounts of growth/respiration. Similar to Smith & Smith's (2015) comments about tropical areas having high productivity compared to other regions, McPherson et al. (2016) showed that trees grown across the United States gained the most carbon when grown in the southeastern United States, although the tree in the Pacific Northwest had gained among the largest amount of carbon. Among urban/community trees across the United States, Washington's average carbon sequestration level was somewhere in the middle (Nowak et al., 2013).

Figure 7 shows the descriptions of an updated version of a common climate classification system: the Köppen-Geiger system. It shows that the Seattle area has a Csb climate, meaning it is temperate (not averaging below freezing any month of winter), has a warm summer (has 4 or more months a year with an average temperature above 10 degrees Celsius/50 degrees Fahrenheit, but not any months averaging over 22 degrees Celsius/71.6 degrees Fahrenheit any month of summer), and has a dry summer (less than 40 mm (1.57 inches) of rain in the driest month of summer as well as a driest month of summer that has less precipitation than the amount of precipitation in the wettest month of the year divided by 3 (Beck et al., adapting from Peel et al., 2007). The variation in summer and winter weather has similarities to a Mediterranean climate, a climate which Smith & Smith (2015) describe as "…[a soil] generally deficient in nutrients, and litter decomposition is limited by low temperatures during winter and low soil moisture during summer. These ecosystems vary in productivity depending on annual precipitation and severity of summer drought" (Smith & Smith, 2015, p. 526). It is unclear if the exact same qualities apply to the Seattle area, but it is true that there are relatively low temperatures during winter and dry summers. Alternatively, the Köppen-Trewartha classification defines the Seattle area as an Oceanic climate, meaning it has 4 – 7 months of at least 10 degrees Celsius/50 degrees Fahrenheit, and the coldest month has an average temperature of 0 Celsius/32 Fahrenheit or higher (Millison, n.d.).

The Portland, Oregon area has a generally similar climate to the Seattle area (Beck et al., 2018; climatedata.org, Millison, n.d.). One study found that the Wilamette Valley had a Net Primary Productivity (the amount of carbon gained by plant photosynthesis minus amount of carbon lost by plant respiration) of approximately 552 grams of carbon per square meter per year, and a Net Ecosystem Productivity (the Net Primary Productivity minus respiration from decomposer and consumer organisms) of 146 grams of carbon per square meter per year (due in large part to successful agriculture). Nearby forested regions had Net Primary Productivity ranging from 681 – 840 grams of carbon per square meter per year (approximately 2.5 – 3.1 kilograms of carbon dioxide per square meter per year), and Net Ecosystem Productivity ranging from 114 – 197 grams of carbon per square meter per year (approximately 0.42 – 0.72 kilograms of carbon dioxide per square meter per year) based on data from 1980-2002 (Turner et al., 2007). These numbers can be compared to carbon sequestration levels in section 2.2.

Figure 7

Elucidation of a Slightly Modified Version of the Köppen-Geiger Climate Classifications

1st	2nd	3rd	Description	Criterion[a]
A			Tropical	Not (B) & $T_{cold} \geq 18$
	f		- Rainforest	$P_{dry} \geq 60$
	m		- Monsoon	Not (Af) & $P_{dry} \geq 100\text{-}MAP/25$
	w		- Savannah	Not (Af) & $P_{dry} < 100\text{-}MAP/25$
B			Arid	$MAP < 10 \times P_{threshold}$
	W		- Desert	$MAP < 5 \times P_{threshold}$
	S		- Steppe	$MAP \geq 5 \times P_{threshold}$
		h	- Hot	$MAT \geq 18$
		k	- Cold	$MAT < 18$
C			Temperate	Not (B) & $T_{hot} > 10$ & $0 < T_{cold} < 18$
	s		- Dry summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Cs) or (Cw)
		a	- Hot summer	$T_{hot} \geq 22$
		b	- Warm summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold summer	Not (a or b) & $1 \leq T_{mon10} < 4$
D			Cold	Not (B) & $T_{hot} > 10$ & $T_{cold} \leq 0$
	s		- Dry summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Ds) or (Dw)
		a	- Hot summer	$T_{hot} \geq 22$
		b	- Warm summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold summer	Not (a, b, or d)
		d	- Very cold winter	Not (a or b) & $T_{cold} < -38$
E			Polar	Not (B) & $T_{hot} \leq 10$
	T		- Tundra	$T_{hot} > 0$
	F		- Frost	$T_{hot} \leq 0$

Table 2. **Overview of the Köppen-Geiger climate classes including the defining criteria.** Adapted from Peel *et al.*[21]. [a]Variable definitions: MAT = mean annual air temperature (°C); T_{cold} = the air temperature of the coldest month (°C); T_{hot} = the air temperature of the warmest month (°C); T_{mon10} = the number of months with air temperature >10 °C (unitless); MAP = mean annual precipitation (mm y^{-1}); P_{dry} = precipitation in the driest month (mm $month^{-1}$); P_{sdry} = precipitation in the driest month in summer (mm $month^{-1}$); P_{wdry} = precipitation in the driest month in winter (mm $month^{-1}$); P_{swet} = precipitation in the wettest month in summer (mm $month^{-1}$); P_{wwet} = precipitation in the wettest month in winter (mm $month^{-1}$); $P_{threshold} = 2 \times MAT$ if >70% of precipitation falls in winter, $P_{threshold} = 2 \times MAT + 28$ if >70% of precipitation falls in summer, otherwise $P_{threshold} = 2 \times MAT + 14$. Summer (winter) is the six-month period that is warmer (colder) between April-September and October-March.

Note. From "Present and future Köppen-Geiger climate classification maps at 1-km resolution," by H.E. Beck, N.E. Zimmermann, T.R. McVicar, N. Vergopolan, A. Berg, & E.F. Wood, 2018, *Scientific Data, 5,* p. 5 (https://doi.org/10.1038/sdata.2018.214). CC BY 4.0.

Beck et al. (2018) explained slight modifications to the classic Köppen-Geiger climate classifications as follows:

> This classification is identical to that presented by Köppen in 1936[1] with three differences. First, temperate (C) and cold (D) climates are distinguished using a 0 °C threshold instead of a 3 °C threshold, following the suggestion of Russell[30]. Second, the arid (B) sub-climates W (desert) and S (steppe) were identified depending on whether 70% of precipitation occurred in summer or winter. Third, the sub-climates s (dry summer) and w (dry winter) within the C and D climates were made mutually exclusive by assigning s when more precipitation falls in winter than in summer and assigning w otherwise. Note that the tropical (A), temperate (C), cold (D), and polar (E) climates are mutually exclusive but may intersect with the arid (B) class. To account for this, climate type B was given precedence over the other classes. (p. 2)

Carbon sequestration patterns today will not stay the same. The Puget Sound region will experience warmer temperatures, significant seasonal and annual precipitation and temperature variability, more and heavier rainfalls with flooding, rising sea levels, and ocean acidification, all with their own consequences (Climate Impacts Group, 2015). What this means for carbon sequestration in the area is uncertain. The growing season could increase in length and the CO_2 fertilization effect could increase vegetative growth, while drought and fires could damage or kill more vegetation (Climate Impacts Group, 2015). Green roofs could be exposed to many of these contrasting effects, though green roofs are relatively safe from fires. Future climate scenarios should be considered when selecting green roof plants in Seattle.

2.1.7: Summary

While rooftops can sometimes be considered as relatively harsh conditions for plants, with often little to no shade and lots of wind, it is also the case that rooftops can be optimal sequestration conditions for the right kinds of plants, or for plants with the right kinds of care. This section suggests that shade-intolerant plants can thrive on rooftops due to unhindered access to sunlight, maximizing the rate of photosynthesis relative to other locations. Sufficient airflow allows for exchange of CO_2 and water vapor, increasing carbon uptake which will already be increasing due to the CO_2 fertilization effect. While extended dry periods can potentially reduce growth of plants, the plants also can receive rain without blockage from anything above them (and the green roof's drainage system, in addition to the greater air flow, can help prevent over-saturated soil). Since it is shown that larger plants absorb more carbon than smaller plants, and shade-intolerant plants absorb more carbon in non-shady conditions, large shade-intolerant plants could do particularly well on a green roof. Additionally, it could still be possible to layer the green roof with plants, such that shade-tolerant plants could be planted underneath shade-intolerant plants, increasing the amount of sequestration per unit of area.

2.2: Empirical

With an understanding of the fundamentals of CO_2, its exchange between plants and air, and factors which influence the sequestration of carbon from the atmosphere into plants, research can be explored which studied and quantified carbon sequestration on green roofs.

Before examining the scientific research on carbon sequestration in green roofs, a point should be clarified regarding measurements of carbon (C) vs. carbon dioxide (CO_2). As is shown in section *2.1.2*, plants absorb CO_2 from the air and, through photosynthesis, the C atom is eventually integrated into other molecules such as sugars and proteins. In research on carbon sequestration, researchers sometimes measure sequestration in terms of grams (g) or kilograms (kg) of C, and sometimes they measure it in terms of g or kg of CO_2. Measuring carbon is describing the amount of carbon that has been integrated into the plant, while measuring carbon dioxide is describing the amount of CO_2 that has been removed from the atmosphere and transformed into other forms. They are simply different ways of measuring carbon sequestration. For every 1 unit of mass of C, there are 3.67 units of CO_2 because of its molecular weight (McPherson et al., 2016). So 1 g or kg of C can be converted to 3.67 g or kg of CO_2, and vice versa. Additionally, a point should be made to clarify a particular notation commonly seen throughout this section and beyond: “m^{-2}” means “per square meter.” Sequestration measurements are typically shown as “kg C m^{-2}” or “kg CO_2 m^{-2}”, which mean “kilograms of carbon per square meter” or “kilograms of carbon dioxide per square meter.” The research below is shown with the units those authors used for measuring sequestration. In Chapter 3 (Methods), all relevant sequestration results from the empirical literature to be used for Seattle’s carbon sequestration estimation is standardized into kg CO_2 m^{-2}.

2.2.1: Green Roofs and Carbon Sequestration

Getter et al. (2009) produced an early study examining the carbon sequestration of green roofs; they studied an extensive green roof with four species of *Sedum* plants (which are typical extensive green roof plants), each of the 20 plots had one of these species, while the control plots had only substrate (i.e., soil). Substrate depth was 6.0 cm. Artificial irrigation occurred within the first three months and weeding occurred as needed on a monthly basis. Measurements were made of the aboveground plant biomass, belowground plant biomass, and substrate to determine their carbon content at 3 different points throughout each of two growing seasons; additionally, the initial substrate carbon content was measured. Results showed that overall, the entire green roof system studied sequestered 375 g C m^{-2}. The authors state that if all roofs in the Detroit metropolitan area's commercial and industrial areas had this vegetation, the green roof would sequester 55,152 tons of carbon by the end of the second growing season- what they compared to as eliminating emissions from 10,000 midsized SUVs/trucks for one year (Getter et al., 2009).

A later analysis of several types of rooftop landscapes were designed and tested to determine carbon sequestration and carbon storage over three growing seasons in East Lansing, Michigan (Whittinghill et al., 2014). Measurements were taken for aboveground biomass, belowground biomass, and soil/substrate; these three categories were also summed to create a total carbon content calculation. Green roof soil depth was 10.5 cm. Green roof irrigation was thrice daily in 2009 and once daily during 2010 and 2011. There was an extensive green roof (*Sedum* succulents), a prairie mix roof, and an herbaceous perennials and grasses roof (i.e., a meadow). One inch of mulch was added to the rooftop with herbaceous perennials and grasses, primarily for weed control.

Deciduous, needle-leaf evergreen, and broadleaf evergreen shrubs had their carbon content measured on the ground, but not on the roofs; these could provide partial insight into the amount of carbon that shrubs might store on the roof, as well as a point of comparison to the rooftop plots. Other plant plots on the ground had analogous species to the rooftop plots; these could provide comparative insights. The ground-level plants had an unknown soil depth, and irrigation was only during the plant-establishing phase in the first growing season, with none afterwards. Three inches of mulch were added to the shrubs, and 1.5 inches for the ground-level herbaceous perennials and grasses.

At the end of the third growing season, "[a]fter adjusting for initial substrate carbon content (3.15 kg C m^{-2}) the *Sedum*, prairie and ornamental green roofs contained 4.67, 5.64, and 65.25 kg C m^{-2}, respectively…" (Whittinghill et al., 2014, p. 47). After the end of second growing season (the same amount as time as the Getter et al. (2009) study), there was respectively 2.65, 1.5, and 34.11 kg C m^{-2}; the result in Getter et al.'s (2009) study after this period of time was 0.375 kg C m^{-2} (its most analogous rooftop plot here was the *Sedum* rooftop, which amassed approximately seven times as much total carbon content in the same time period. Whittinghill et al. (2014) posit that both deeper soil and irrigation played a role, as well as potentially the biodiversity of the green roofs here, compared to the green roofs in Getter et al.'s (2009) study which had *Sedum* species separated out for the purposes of their study.

Ground-level deciduous shrubs and herbaceous perennials/grasses had similar total carbon content as the rooftop herbaceous perennials and grasses. Needle-leaf evergreen shrubs had less total carbon content than the rooftop herbaceous perennials and grasses. Broadleaf evergreen shrubs had the most total carbon content. It must be noted that the ground-level landscapes had more soil carbon content than on the rooftops. The authors suggest that green roofs have greater drainage which may have led to more soil carbon content leaving the roof than on the ground below the plants; it is unclear if this accounted for all of the significant soil carbon differences.

As alluded to above, the rooftop herbaceous perennials and grasses had almost same amount of total carbon content as the ground-level version—slightly less. Without considering the soil, the rooftop has significantly more carbon. However, the ground-level succulent garden had almost 73% more total carbon content than the rooftop version (~10% more when not considering the soil), and the ground-level prairie mix had about 53% more than the rooftop version (~34% when not considering the soil).

Notably, the green roofs gained significant carbon content between the end of the second growing season and the end of the third growing season, indicating that longer-term studies may yield more accurate insights into green roof carbon sequestration capacity.

In Chengdu, China, a one-year experiment was done from July 2012 to July 2013 with green roofs with combinations of different soil types, soil depths, and plant types. Soil type was either a natural soil or a natural soil mixed with dried sewage sludge soil (MSSS). Soil depth was either 20 cm, 25 cm, or 30 cm. Plants were either grass, ferns, or deciduous shrubs. The MSSS substrate stored more carbon than the natural soil, though sequestration rates were similar between the two soil types. Among the plants, the carbon storage and carbon sequestration was highest in the deciduous shrubs, then the grasses, then the ferns, though in the deeper natural soils, the ferns stored and sequestered more than the grasses. Deciduous shrubs had highest storage and sequestration in 25 cm soil depth in the MSSS soil, and in the natural soil the 20 cm had the highest levels. Grass had similar levels across MSSS soil depths, with 20 cm slightly less; in natural soil, the grass in 20 cm had the highest levels. In MSSS soil, ferns had similar in 25 and 20 cm, higher than 30 cm; in natural soil, ferns had the highest levels in 30 cm soil. Regarding plant storage and sequestration across soil types, deciduous shrubs and grasses had higher levels in MSSS soil than natural soil, while ferns had higher levels in natural soil than MSSS soil.

The total plant + soil carbon storage for L. spicata, N. auriculata, and L. vicaryi in natural soil was 9.91, 9.75, and 12.18 kg C m^{-2}, respectively. The carbon total plant + soil carbon storage for L. spicata, N. auriculata, and L. vicaryi in MSSS soil was 14.48, 14.32, and 16.75 kg C m^{-2}, respectively. The total plant + soil carbon sequestration rate for L. spicata, N. auriculata, and L. vicaryi in natural soil was 4.85, 4.81, and 7.11 kg C m^{-2} per year, respectively. The total plant + soil carbon sequestration rate for L. spicata, N. auriculata, and L. vicaryi in MSSS soil was 4.77, 4.73, and 7.03 kg C m^{-2} per year, respectively. These are across all soil depths, meaning an average of 25 cm (Luo et al., 2015).

Another carbon sequestration study was performed in a Mediterranean city in Spain named Murcia, with extensive green roofs that had: a depth of either 5 cm or 10 cm; a substrate made of either a combination of compost & bricks or a combination of compost, soil, & bricks; irrigation or no irrigation (aside from the first month where all plots received irrigation); and either an herbaceous perennial that becomes 10-100 cm or an annual grass reaching 8 – 80 cm. The experiment was 10 months long, from October 2012 to July 2013.

Carbon sequestration was measured in the substrate as well as aboveground plant biomass. Carbon increased in all plot conditions, especially with irrigation (most strongly in compost-soil-brick substrate). Plants always, and substrates almost always, sequestered larger amounts of carbon when the substrates were deeper. The annual grass plots had more carbon sequestered both by the plants and by the soil than the herbaceous perennial. This is in large part due to the annual grass withering and going into the soil before the new generation comes up. Even with decomposition process that would release most of the dead plants as atmospheric CO_2, so long as the green roof lives, there will be undecomposed grass in the soil which will add to the carbon store. There was also more widespread grass coverage on the plots than with the herbaceous perennial.

Overall, the mean carbon sequestered by all of the annual grass plots (as shown in data: both irrigated and non-irrigated combined, and both substrate types, average depth 7.5 cm (~3 inches, a moderate depth for SGF's shallowest green roof category)) was 1.058 kg C m^{-2}, and the mean carbon sequestered by all of the herbaceous perennial plots was 0.373 kg C m^{-2}. The mean carbon sequestered by all of the compost-brick plots (as shown in data; both irrigated and non-irrigated combined, both plant types, average depth 7.5 cm), was 0.426 kg C m^{-2}, and the mean carbon sequestered by all of the compost-soil-brick plots was 1.005 kg C m^{-2}. Mean carbon sequestered across all irrigated/non-irrigated, plant types, and soil types was 0.716 kg C m^{-2}. The best sequestration was for the 10-cm irrigated compost-soil-brick annual grass, which had 2.346 kg C m^{-2}. Overall, they recommend balancing plant growth ability with weight, and say that combining both plant types could lead to more overall green roof coverage (Ondoño et al., 2016a). It is unclear why belowground plant biomass was not measured. Also, generally speaking, when plots were irrigated, those with the deeper substrates had less water-soluble carbon content drain out of the soil.

Another study by the same group (Ondoño et al., 2016b) looked at two new species and two additional types of substrate (plus those in the other study), all at 10 cm depth and with the same weekly irrigation. One plant was a small-medium perennial species that can have stems up to 150 cm long. The other plant was another perennial which can get one foot tall by four feet wide. Both are often found in semi-arid, coastal Mediterranean areas. The soil types tested, in addition to the compost-brick and compost-soil-brick from the other study, were compost-silica sand-brick, and compost-silica sand-soil. The experiment was 10 months long, from November 2013 to August 2014. Carbon sequestration was just measured for soil (not plant biomass) due to experimental constraints.

All those substrates which contained soil sequestered carbon. Those which did not contain soil did not, except for the compost-silica sand-brick substrate (and of that substrate, only the substrate in one of the plants gained both organic carbon and total carbon, while the other lost organic carbon but gained carbon overall). Of those substrates that sequestered carbon, the range was from 0.028 kg C m^{-2} to 1.064 kg C m^{-2}. Excluding the compost-brick substrates, which lost carbon, the substrate for the first and second perennial plants described above sequestered 0.418 and 0.524 kg C m^{-2}, respectively; the average substrate carbon sequestration for all of these plots was 0.471 kg C m^{-2}. The average sequestration of all plots with soil in their substrates was 0.6125 kg C m^{-2}. Regarding organic carbon sequestered, the range sequestered across those substrates that indeed sequestered organic carbon was from 0.109 kg C m^{-2} to 0.353 kg C m^{-2}, with an average of 0.192 kg C m^{-2}. The substrate for the first and second perennial plants described above sequestered an average of 0.245 kg C m^{-2} and 0.1115 kg C m^{-2}, respectively. The average organic carbon sequestration of all plots with soil in their substrates was 0.1775 kg C m^{-2}.

Substrates with soil did have more water-soluble carbon leach out of the substrate after significant water events, though those amounts are not counted above (Ondoño et al., 2016b).

A study in southern Mexico City examined carbon sequestration of two species of *Sedum* succulents (Collazo-Ortega et al., 2017). The 42 square meter green roof was installed in 2009. The substrate was a 1:1 mix of a drainage-promoting tepojal, and compost. The substrate was 10 cm depth. Only an initial irrigation was provided during the experiment. One species of *Sedum* grows to 50-100 cm in a bushy form, and the other from 15-20 cm in an herbaceous form. Once the green roof was installed in November 2009, the measurements took place in that month and each month through November 2010, one year later. Carbon sequestration was measured through analyzing gas exchange of the leaves, and validated through plant tissue analysis.

The bushy *Sedum* was shown to sequester more carbon throughout the period; however, it was not statistically significant. Interestingly, carbon sequestration was the most during February and March- part of the dry season which touches on both the cooler and warmer parts of the year. Overall, combining the two species, the annual carbon sequestration was measured to be 371.27 g C m^{-2} per year (Collazo-Ortega et al., 2017).

A one-year study in Berlin from September 1, 2014 through August 31, 2015 examined gas exchanges on a large (8,600 m^2) extensive green roof which had a combination of *Sedum* and herbaceous plants. The plant heights ranged from 10 to 30 cm. The substrate depth was 9 cm. Irrigation did not occur during this experiment. The green roof sequestered a net of 0.085 kg C m^{-2} per year, or 0.313 kg CO_2 m^{-2} per year. It was recommended to irrigate during dry spells in order to improve sequestration; it was also noted that this was a drier year than usual, which likely underestimated the average sequestration level. It is also unclear how sequestration would vary as the plants grew older- the green roof was created in 2012 (Heusinger & Weber, 2017a).

Heusinger & Weber (2017a) also cite a study of green roof carbon sequestration reported as having a *Sedum* green roof in Canada which sequestered a net of 0.440 kg C m^{-2} per year (Heusinger & Weber, 2017a; Skabelund et al. 2015).

A study in Chiba, Japan examined carbon sequestration of three types of plants- a warm-season grass, an evergreen perennial, and a *Sedum* species. These were all placed in a substrate of 5 cm depth. Plant cuttings were grown for three months, and then acclimated onto a rooftop for three weeks before the start of the one-year experiment (October 20, 2014 to October 20, 2015). The grass and perennial species were regularly irrigated (the 'wet') category. The *Sedum* species was assigned to either the wet condition, a 'dry' condition with less frequent watering, or a non-irrigation treatment with no watering at all. The ‘wet’ and ‘dry’ conditions are described as follows:

> Plants of the wet treatment group were watered once a week from January to March, once every two days from April to June, every day from July to September, and once every two days from October to December. The plants of the dry treatment group were not watered from January to March, and watered once every two weeks from April to June, once a week from July to September, and once every two weeks from October to December. (Kuronuma & Watanabe, 2017, p. 17)

All plots received fertilizer twice: once in June and once in August. The aboveground biomass, belowground biomass, and substrate were all measured for their carbon content before and after the experiment.

Aboveground biomass in all plant types and conditions gained significant carbon throughout the year. *Sedum* ‘wet’ and ‘dry’ conditions gained similar amounts of carbon, both significantly more than the non-irrigated condition. Substrate in all plant types and conditions increased, and all increased significantly except the evergreen perennial. There were no significant differences in substrate carbon content between the different *Sedum* conditions.

Regarding total carbon sequestration over the year for each plant type and condition (combining plants and substrate), the warm-season grass plots gained 0.670 kg C m^{-2} per year, the evergreen perennial plots gained 0.282 kg C m^{-2} per year, and the *Sedum* plots gained 0.336 kg C m^{-2} per year, 0.364 kg C m^{-2} per year, and 0.276 kg C m^{-2} per year for the wet, dry, and non-irrigation conditions, respectively.

Another study by the same authors above and others in Chiba, Japan examined four types of plants- three species of grass and one type of flowering *Sedum*, in a substrate of 5 cm depth.

As with the last experiment, plant cuttings were grown for three months, and then acclimated onto a rooftop for three weeks before the start of the one-year experiment (October 20, 2014 to October 20, 2015). The grass plots were all irrigated, and the *Sedum* had both irrigated and non-irrigated plots. Irrigated plants "…were watered once a week from January to March, once every two days from April to June, every day from July to September and once every two days from October to December" (Kuronuma et al., 2018, p. 5). All plots had fertilizer twice- once in June and once in August. Carbon was measured in the plants (not specified but presumably including underground biomass) as well as the substrates.

Carbon was significantly sequestered in all plants, substrates, and conditions. In total, the three different grass species sequestered 0.690 kg C m^{-2} per year, 0.751 kg C m^{-2} per year, and 0.671 kg C m^{-2} per year. The irrigated *Sedum* sequestered 0.459 kg C m^{-2} per year, and the non-irrigated *Sedum* sequestered 0.336 kg C m^{-2} per year. Converted to kg CO_2 m^{-2} per year, these are 2.530 kg-CO_2 m^{-2} per year, 2.754 kg-CO_2 m^{-2} per year, 2.459 kg-CO_2 m^{-2} per year, 1.684 kg-CO_2 m^{-2} per year, and 1.232 kg-CO_2 m^{-2}per year. It is suggested that the *Sedum* would have sequestered additional carbon with more nutrients (Kuronuma et al., 2018).

A study in Nanjing, China, following up on Luo et al.'s (2015) study on natural soil versus mixed-natural-sludge soil, examined three soil conditions- sludge, biochar created from sludge, and urban natural soil. Both sludge and biochar are used to recycle municipal solid waste, and while sludge undergoes its own physiochemical manipulations to increase safety, biochar is a method which dries and then burns, without oxygen, sludge into a safer carbon-storing substrate (Luo et al., 2015; U.S. Department of Agriculture, 2017). Both can be used for plants (Chen et al. 2018).

The experiment took place from June 2016 to May 2017. A type of *Sedum* species was used. Substrate depth was 25 cm. There were nine substrate conditions in total: just natural soil, and then natural soil mixed with 5%, 10%, 15%, or 20% of sludge or biochar. Plants (presumably both aboveground and belowground biomass) and soil were both measured for carbon content.

Substrate carbon and plant carbon were greater in both sludge and biochar conditions compared to the natural-only soil, and biochar had more average carbon than sludge. Greater percentages of biochar or sludge increased the total carbon stocks, except for the upper percentages of biochar: 20% biochar had less substrate and plant carbon than 15% biochar, likely due to properties related to temperature, water, and consequent plant growth.

Carbon in all substrates increased over time. Carbon increased more in the biochar conditions than sludge conditions. Regarding plants, biomass increased more on average with biochar than with sludge, and both more than urban natural soil. The plants themselves had a carbon storage of 1.15 kg C m^{-2} in the urban natural soil, while there was a range of 1.65 to 2.86 kg C m^{-2} for plants with sludge soil, and a range of 2.12 to 3.57 kg C m^{-2} for plants with biochar soil.

For the green roof as a whole (substrate and plants), sludge green roofs sequestered between 6.8 and 8.8 kg C m^{-2} per year, and biochar green roofs sequestered between 7.7 and 11.9 kg C m^{-2} per year. The carbon sequestered for the green roof with urban natural soil was approximately 6.39 kg C m^{-2} per year (Chen et al., 2018).

A recent study in Wuxi, China examined green roofs from June 2017 to March 2018. Stonecrop, a standard type of *Sedum*, was used to measure carbon sequestration (Cai, Feng, Yu, Xiang, & Chen, 2019). It was not clear from the article how deep the substrate was or what the irrigation strategy was. Unlike previous studies mentioned, this study used a portable photosynthesis/respiration counter for the Stonecrop's leaves, rather than analyzing the carbon in the biomass and substrates. This gas exchange tool determined that the stonecrop would sequester 1.79 kg CO_2 /m^{-2} per year (Cai et al., 2019).

There is a burgeoning collection of carbon sequestration research for green roofs. It is primarily focused on extensive roofs because they are the most common and easiest green roofs to install and maintain. There are also several experimental soils and plants under consideration in order to try maximizing carbon sequestration, including sewage sludge and biochar; results suggest these would be more successful than natural soil/compost in terms of sequestering carbon. The results from the green roof carbon sequestration studies in this section provide a relatively new yet diverse foundation for the potential sequestration capacity of green roofs. With a mindfulness of climate type, plant type, plant age, soil type, soil depth, specific location, maintenance habits, and other study characteristics, these studies can collectively begin to demonstrate average sequestration rates that can be used to inform other analyses, including this thesis. Similar studies in Seattle would provide significantly more relevant data, but in the meantime these studies together can help provide the basis for estimates for Seattle's green roof carbon sequestration. In Chapter 3, the empirically-determined green roof sequestration rates considered relevant for the thesis experiment are succinctly collected, summarized, and standardized for this purpose.

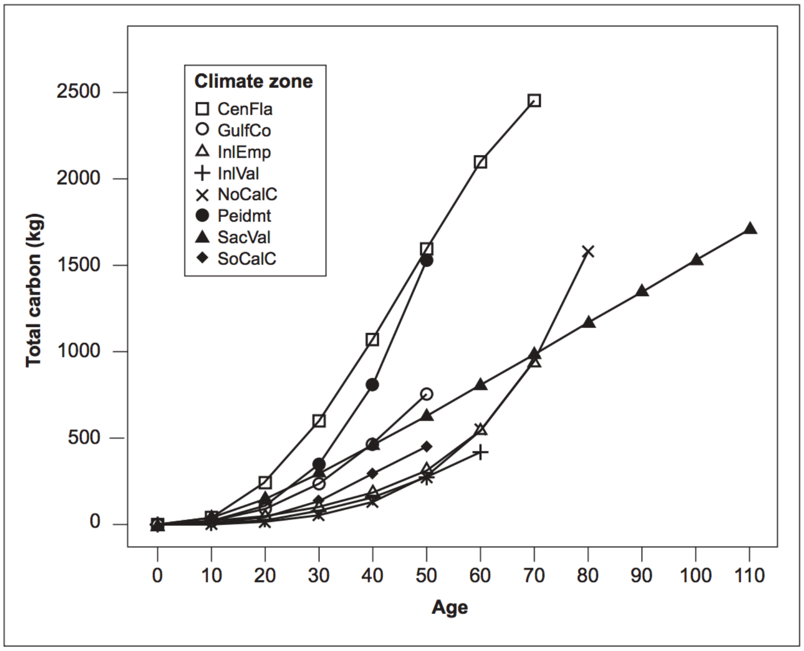
2.2.2: Trees and carbon sequestration

The presence of trees on green roofs signals the importance of understanding trees' carbon sequestration potential. It should first be noted that there is no direct comparison available of carbon sequestration between trees on the ground and trees on green roofs; the only vegetative comparisons between these levels are for (1) succulent & rock garden, (2) native prairie mix, and (3) herbaceous perennials and grasses on the ground level and on green roofs. The ground-level versions all contained more carbon, yet all lost carbon throughout the 26-month experiment, while all of the green roof versions sequestered carbon throughout the experiment (Whittinghill et al., 2014). It is unclear if, and how significant, a difference in carbon sequestration may be between same-species trees on the ground and on a roof. It would make sense that younger trees could have similar growth; perhaps the rooftop tree would tend to sequester more carbon initially, given appropriate irrigation/nutrients/maintenance, due to more sunlight. However, potential spatial constraints on root growth on the roof tree due to container size or relatively shallow soil depth could indicate greater carbon sequestration by the ground-level tree in the long run. This hypothesis would need to be tested to be confirmed.

It is the case that different conditions—climatic as well as site—influence tree growth. Figure 8 is an image from the United States Department of Agriculture's *Urban Tree Database and Allometric Equations* technical report showing estimated carbon based on measurements of Southern Magnolias, a type of tree which will be discussed and analyzed in terms of carbon sequestration in the Appendix section due to its presence in Seattle (including on buildings), in locations across the U.S (McPherson et al., 2016).

Figure 8

Carbon Content of Southern Magnolias (Magnolia Grandiflora) over Time in Different Cities Across the United States

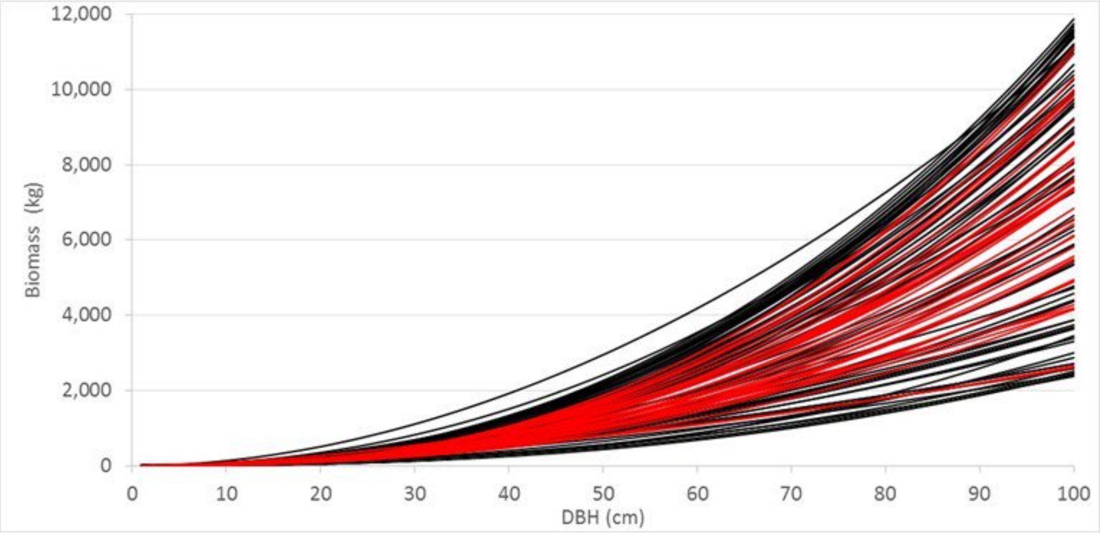


Note. The Pacific Northwest climate (represented by Longview, Washington) was not included for the Southern Magnolia analysis. Based on data elsewhere in this USDA technical report, the Southern Magnolia cultivar used is likely different and significantly larger than cultivars commonly found in the Pacific Northwest. Detailed climate data is provided in the report for each of the cities shown as representative of particular U.S. climates. CenFla = Orlando, Florida; GulfCo = Charleston, South Carolina; InlEmp = Claremont, California; InlVal = Modesto, California; NoCalC = Berkeley, California; Piedmt = Charlotte, North Carolina; SacVal = Sacramento, California; SoCalC = Santa Monica, California. From *Urban Tree Database and Allometric Equations*, by E.G. McPherson, N.S. van Doorn, & P.J. Peper, 2016, United States Department of Agriculture (https://www.fs.fed.us/psw/publications/documents/psw_gtr253/psw_gtr_253.pdf). Copyright information is unclear/unavailable.

As is also indicated by Figure 8, the same tree grown in different conditions has relatively similar (and small) amounts of carbon early in the tree's life, especially in the first 5-10 years; other trees show the same general pattern (McPherson, van Doorn, & Peper, 2016). The same general pattern also holds true across many species of trees, as shown in Figure 9.

Figure 9

Modeled Growth Patterns of Various Tree Species

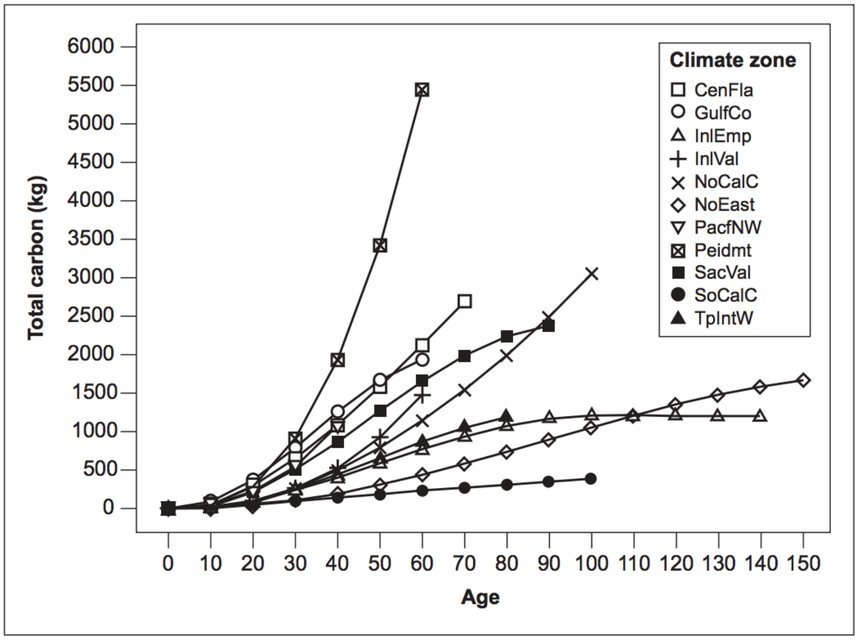


Note. Certain measurements of trees over time, such as the Diameter of the trunk at Breast Height (DBH), can be used to create biomass or growth equations in order to estimate total tree biomass or carbon. Here, an increase in DBH (meaning a larger and by proxy generally older tree) is shown to usually have a greater-than-linear impact on tree biomass. These differences become more apparent the larger/older the tree becomes. Individual trees have their own lines, due in part to unique sizes but also factors like unique wood densities. It is estimated that total tree carbon is approximately 50% of a tree's dry-weight biomass, which is shown here. Note: The red and black colors only indicate current or future usage, respectively, within i-Tree From "New Carbon Equations and Methods, 2021", by the i-Tree Cooperative, 2021, i-Tree (https://www.itreetools.org/support/resources-overview/i-tree-methods-and-files/new-carbon-equations-and-methods-2020). In Public Domain.

While the trend of divergence over time in carbon content across species, and within species across growing conditions, generally holds true, it is not always the growth trajectory for trees, as is shown in Figure 10.

Figure 10

Carbon Content of Sweetgum Trees (Liquidambar styraciflua) over Time in Different Cities Across the United States



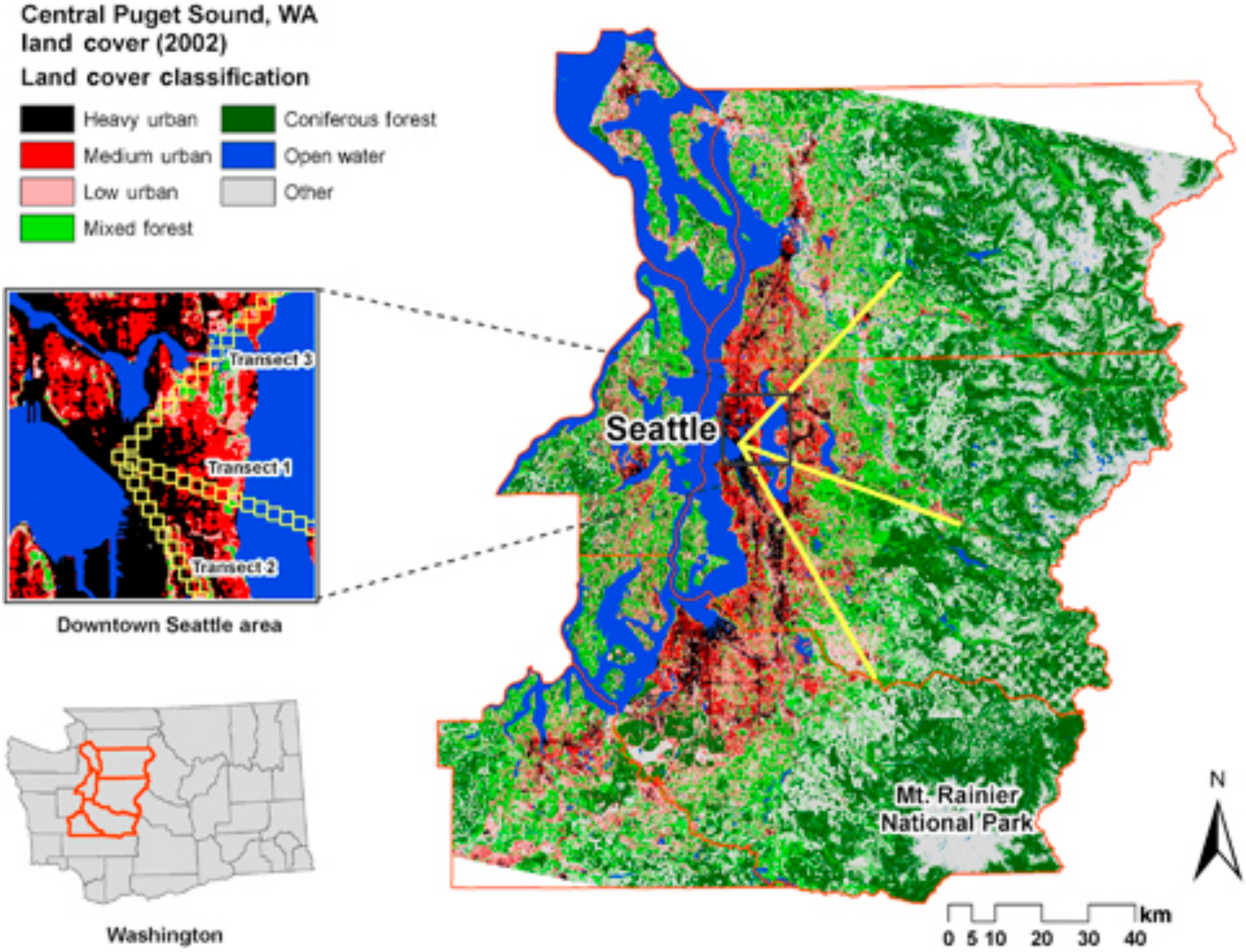
Note. CenFla = Orlando, Florida; GulfCo = Charleston, South Carolina; InlEmp = Claremont, California; InlVal = Modesto, California; NoCalC = Berkeley, California; NoEast = Queens, New York City, New York; PacfNW = Longview, Washington; Piedmt = Charlotte, North Carolina; SacVal = Sacramento, California; SoCalC = Santa Monica, California; TpIntW = Boise, Idaho. From *Urban Tree Database and Allometric Equations*, by E.G. McPherson, N.S. van Doorn, & P.J. Peper, 2016, United States Department of Agriculture (https://www.fs.fed.us/psw/publications/documents/psw_gtr253/psw_gtr_253.pdf). Copyright information is unclear/unavailable.

Nowak et al. (2013) examined all trees in urban and community areas across the U.S., and estimated that Washington State's urban/community areas as a whole had a gross carbon sequestration rate of 0.258 kg C m^{-2} per year, and a net sequestration rate (gross carbon sequestration minus decomposition) of approximately 0.191 kg C m^{-2} per year. This translates to a gross sequestration of 0.947 kg CO_2 m^{-2} per year, and a net sequestration of 0.701 kg CO_2 m^{-2} per year. Tree cover of urban/community areas was estimated using aerial photographs from approximately 2005 (Nowak & Greenfield, 2012; Nowak et al., 2013).

Regarding carbon storage and not carbon sequestration, Nowak et al. (2013) also converted data from Hutyra et al.'s (2011) analysis of the Seattle region's aboveground live carbon stock into kg C m^{-2}: in areas classified as Heavy Urban, the 6% of the land that was canopy cover had 3.3 kg C m^{-2}; in areas classified as Medium Urban, the 21% of the land that was canopy cover had 7.1 kg C m^{-2}; in areas classified as Low Urban, the 31% of the land that was canopy cover had 11.6 kg C m^{-2}. These translate to 12.11 kg CO_2 m^{-2}, 26.06 kg CO_2 m^{-2}, and 42.57 kg CO_2 m^{-2}, respectively. Hutyra et al. (2011) performed field analyses of woody biomass (mostly live biomass but also dead/decaying and built woody biomass) along transects in the Seattle region based upon initial land classifications. These transects and land classifications are shown in Figure 11.

Figure 11

2002 Land Cover Classification of the Seattle Region and Three Transects Analyzed by Field Inspection



Note. From "Terrestrial carbon stocks across a gradient of urbanization: a study of the Seattle, WA region," by L.R. Hutyra, B. Yoon, & M. Alberti, 2011, *Global Change Biology, 17*, p. 786 (https://doi-org.offcampus.lib.washington.edu/10.1111/j.1365-2486.2010.02238.x). Copyright 2010 by Blackwell Publishing Ltd.

Trees were included if they had a DBH of at least 5 cm. Hutyra et al. (2011) state, "Larger trees (≥20 cm DBH) accounted for the vast majority of the total biomass (95%), though smaller trees (≥5 cm and <20 cm DBH) were much more common (2011 trees, 62% of stems)" (p. 789). Understory vegetation was included in the field analyses, so long as they met the size qualifications.

Tenneson (2013) found, when measuring vegetation with 5 cm DBH or higher on single-family parcels in urban (rather than suburban) areas of King County, Washington that on average 13 Megagrams of C per acre were stored in aboveground vegetation, estimated from tree biomass equations. Deciduous trees with small size potential (a mature height of 30 feet or less) stored ~2.5 Megagrams (2,500 kg) of C per acre averaged out across the urban yards. It was difficult to determine how much carbon was stored by evergreen trees with small size potential; it was so small on the graph that it could not be accurately estimated. Tenneson calculated that in urban yards, evergreen trees with small size potential, such as Camellias and Northern White Cedars, individually stored an average of 18 kg of C, and deciduous trees with small size potential, such as Vine Maples and Japanese Maples, individually stored an average of 36 kg of C. DBH for these types of trees with small potential seemed to generally have an average of about 10 cm, though it appeared that Vine Maples and Japanese Maples had certain groups of trees that had DBHs of 40 cm and 50 cm, respectively (Tenneson, 2013).

It is not exactly clear how closely carbon storage and carbon sequestration are tied. Nowak et al. (2013) state that "Sequestration rates will vary locally based on tree sizes, tree health, and growth rates associated with species and site conditions" (p. 235).

Lastly, a report of Seattle's urban forest (which did not include rooftops) estimated that Seattle had approximately 4,350,000 trees and tree-like shrubs, and that these collectively sequestered the equivalent of approximately 141,000 metric tons of CO_2 in 2011.

Trees are ubiquitous in urban environments, and researchers have studied trees in these environments, although not on rooftops. Estimating the carbon sequestration of trees on rooftops would provide a more complete database of green roof sequestration overall, although it is uncertain from the research how tree sequestration levels compare between those on the ground and those on rooftops, and whether an adjustment would need to be made.

2.3: Practice

Several people have examined green roofs in Seattle, working to count, measure, and categorize them. Significant progress has been made over the years, but mapping is far from complete. Additionally, research is still young regarding the specific impacts, interactions, and implications of green roofs in Seattle. This thesis provides a more comprehensive mapping as well as an estimation of carbon sequestration, pushing forward the knowledge of Seattle's green roofs.

In a 2008 University of Washington Master of Urban Planning thesis, an initial analysis was performed on the new local greenspace regulation, the Seattle Green Factor (SGF), which was adopted in December 2006; this is Seattle's most notable and prominent greenspace regulation which includes green roofs (Stenning, 2008). The SGF is described by Stenning (2008) as such:

> According to the code, new building construction is required to meet a minimum landscape or green factor score. Building designers choose from a variety of vegetative elements, weighted from 0.1-0.7. The overall score is determined by the total square footage from each vegetative element, multiplied by the corresponding factor, and divided by the parcel's square footage. (p. abstract)

In 2008, "…[a] minimum score of 0.30 (30%) of the parcel's total area is required for all sites" (Stenning, 2008, p. 38). In its initial adoption, it applied only to most commercial areas outside of downtown (NC1, NC2, NC3, C1, & C2), and "…the SGF [at this point] applies to any new development or redevelopment that exceeds four dwelling units, 4,000 square feet of non-residential uses, or 20 new parking spaces" (Stenning, 2008, p. 33). Downtown Seattle and other areas in the city have their own separate set of regulations for greenspace, and there are also stormwater regulations for which green roofs can be useful (City of Seattle, 2021; McIntosh, 2010; Stenning, 2008).

The SGF has since been expanded to a larger portion of the city, with other minimum scores besides 0.30 going up to 0.6, and with more choice and weight factors for green roofs: Stenning (2008), citing the City of Seattle Department of Planning and Development, showed that green roofs used to get 0.4 points on the SGF for at least 2" and less than 4" of growth medium, and 0.7 points for 4" or more of growth medium. Today, it is still 0.4 points for at least 2" and less than 4" of growth medium, but it is only 0.6 points for 4" to less than 8" of growth medium, and it is 0.8 points for at least 8" of growth medium (City of Seattle, 2021; Seattle Department of Construction and Inspections, n.d.). The SGF in 2008 contained (and still contains in an updated fashion) numerous vegetative elements for a site- various types of ground-level landscaping (lawns, shrubs, trees, etc.), permeable paving, vegetated walls, green roofs, and bonuses for drought-tolerant plants and public-visible landscaping (Stenning, 2008). At this time, green roofs had only one score associated with them- a factor of 0.7 for 4" or more of soil depth.

Stenning (2008), in addition to interviews with city staff and private development staff, gathered city data on SGF projects from January 2007 to April 2008. Stenning found a total of 60 projects which required an SGF worksheet, and was able to gather 42 SGF completed worksheets (and ~49 landscape plans). All of the projects requiring the SGF were in urban villages, with more in Capitol Hill than any other location, and far more in NC3 zoning than other zones, though all zones were represented (and a majority of urban villages were represented- 26 of 39). Green roofs appeared in approximately 50% of the 42 projects that had completed SGF data. This was more common than five other feature categories, and less common than approximately nine categories. However, green roofs took up the second-largest area of all features, at 2.85 acres (Stenning, 2008). Regarding the SGF in general, reducing CO_2 was mentioned in passing, and it was not specific to green roofs (Stenning, 2008).

In 2010, Annika McIntosh completed the first known study directly regarding green roofs in Seattle, prepared for the city and the UW Green Futures Lab; this was based on data from Autumn 2009 (McIntosh, 2010). The purpose of this study was to examine how much green roof space had so far been created in Seattle, and what the implications may be. The emphasis was on green roofs larger than 1,000 square feet, but any were included if found. The methods employed were a combination of "…online research, phone interviews…site visits…viewing the downtown area from the Municipal Tower's upper floor windows or by using online aerial mapping programs to conduct virtual "fly overs." Others were found simply by observation from street level or through informal communication" (McIntosh, 2010, p. 3).

Different types of green roofs were examined: extensive, defined by a soil depth of 2" - 6" and small plants; intensive (also known as rooftop gardens), defined by a soil depth of 6" - 36" and large, biodiverse plants; combination extensive/intensive green roofs, which contain features of both aforementioned categories; urban agriculture roofs; and lids or at-grade green roofs (Cal Anderson Park and Freeway Park are used as examples; these will not be included in the current thesis). Green roofs were also categorized into different sizes, to emphasize different purposes and benefits. Different building uses were also shown- residential, commercial, public, healthcare, and education (McIntosh, 2010). Again, most green roofs were found in densely built areas of the city- located primarily in the central and northern parts of the city.

Based on data up to December 2009, there were 62 green roofs in Seattle, equaling 359,375 square feet. There were 32 extensive roofs equaling 186,270 square feet, 23 intensive roofs equaling 148,069 square feet, and 7 combination extensive/intensive green roofs equaling 25,036 square feet. Additionally, there were 4 agricultural roofs with vegetation in planter boxes, equaling 3,631 square feet (McIntosh, 2010). Once again, there was only a passing mention of carbon sequestration as a benefit of green roofs (McIntosh, 2010).

A UW Community, Environment, and Planning student recently performed an update to McIntosh's (2010) study to determine how many green roofs have been implemented since then (Matza, 2018). Matza (2018) briefly discussed the benefit of carbon sequestration, and cited Whittinghill's (2014) aforementioned paper on the subject. Matza, in collaboration with the city and developers, sought to determine the "…number of green roofs, square feet, type, and motivation to build" (Matza, 2018, p. 16). Data gathering included examination of city records and viewed "…aerial satellite imagery to verify or discover the presence of green roofs" (Matza, 2018, p. 16). Due to time limitations and records complications, not all records were examined. It is not entirely clear by the writing if a list of 1,200 construction projects obtained was specifically since 2010, but this seems to be the case. 350 projects were examined in the time frame of this study, and 15 of those projects had green roofs; these totaled 47,643 square feet. No more information is available (Matza, 2018).

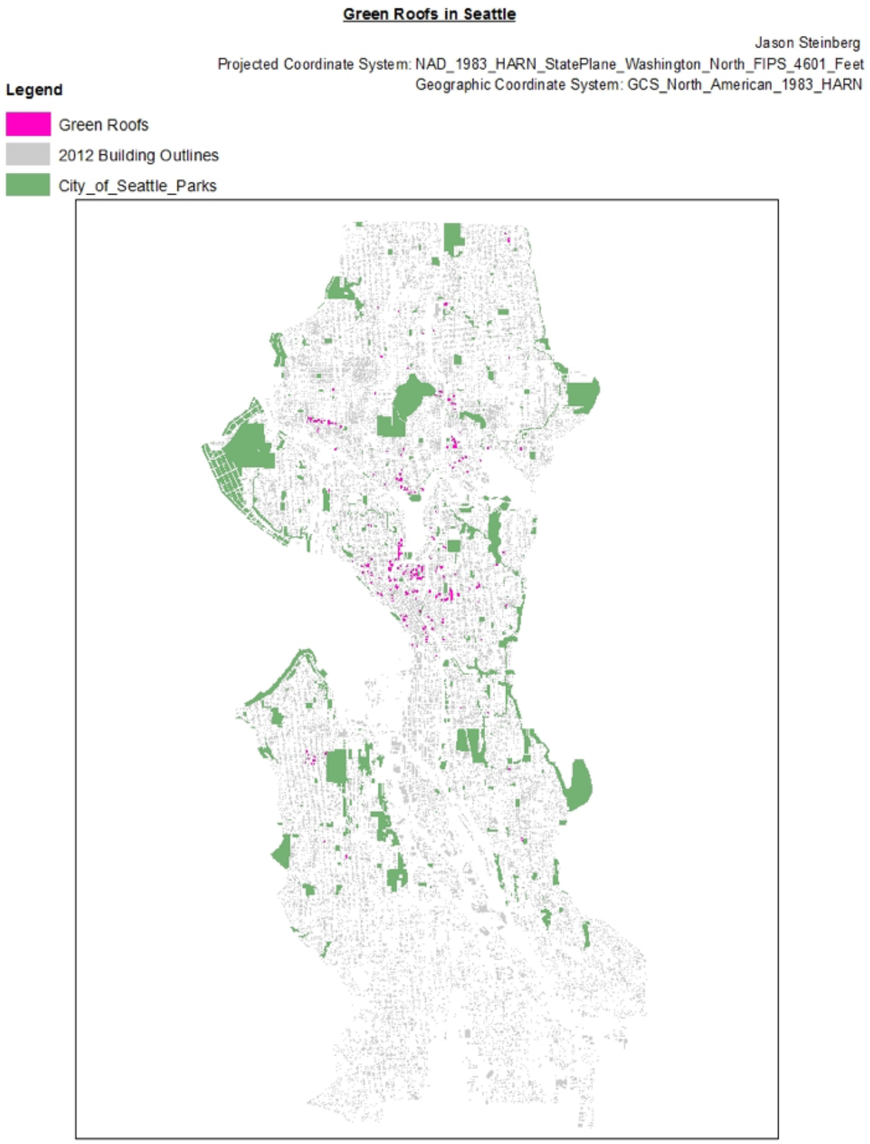
Later in 2018, Steinberg (2018; the author of this thesis) performed an analysis which can be seen as preliminary to this thesis. Unable to acquire previous GIS data from the aforementioned authors, Steinberg visually scanned and manually drew out green roofs in Seattle. Steinberg used Google Maps satellite imagery and an ArcMap satellite base map upon which the green roof polygons were drawn. Steinberg's (2018) search was as follows:

> I searched only for elevated spaces with subjectively significant amounts of greenspace, from roofs that were essentially completely green to built structures slightly above ground that had lots of greenery, to rooftops with several plants. For roofs that only had a few plants, I generally ignored them- I deemed something a green roof if it seemed designed specifically to accommodate at least several pieces of greenery, or at least adorned as such. (pp. 4-5)

Steinberg (2018) found 1,443,705.50 square feet of green roofs or elevated vegetation, equivalent to 0.0518 square miles. Below are Figures 12 and 13 showing the green roofs found throughout the city (note in the first picture, the buildings in the far southern end are not within the city limits):

Figure 12

Green Roofs and Public Green Spaces in Seattle

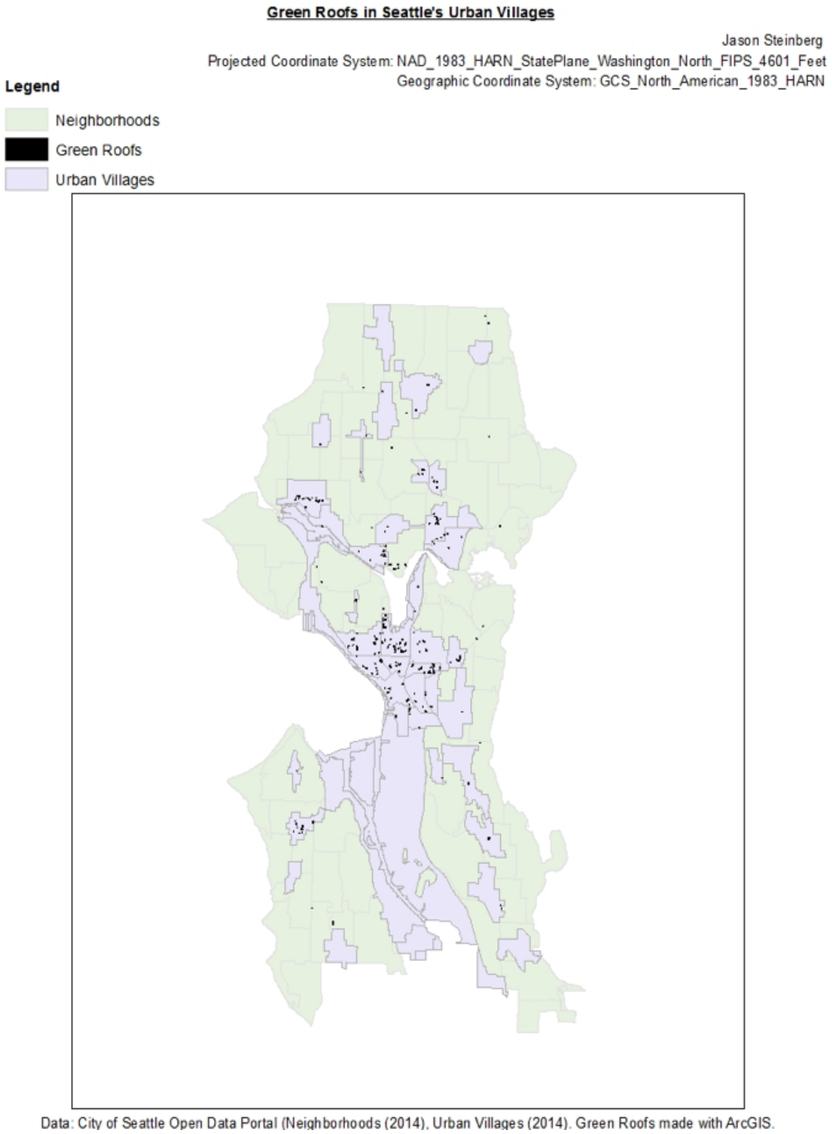


Data: City of Seattle Open Data Portal (City_of_Seattle_Parks, 2012 Building Outlines). Green Roofs made with ArcGIS.

Note. From "Prevalence of Green Roofs in Seattle and Implications for Accessibility to Greenspace," by J. Steinberg, 2018, URBDP 404/504: Introduction to Geographic Information Systems (GIS) at the University of Washington, p. 6. This is my own work for an unpublished class project.

Figure 13

Green Roofs and Urban Villages in Seattle



Data: City of Seattle Open Data Portal (Neighborhoods (2014), Urban Villages (2014). Green Roofs made with ArcGIS.

Note. From "Prevalence of Green Roofs in Seattle and Implications for Accessibility to Greenspace," by J. Steinberg, 2018, URBDP 404/504: Introduction to Geographic Information Systems (GIS) at the University of Washington, p. 9. This is my own work for an unpublished class project.

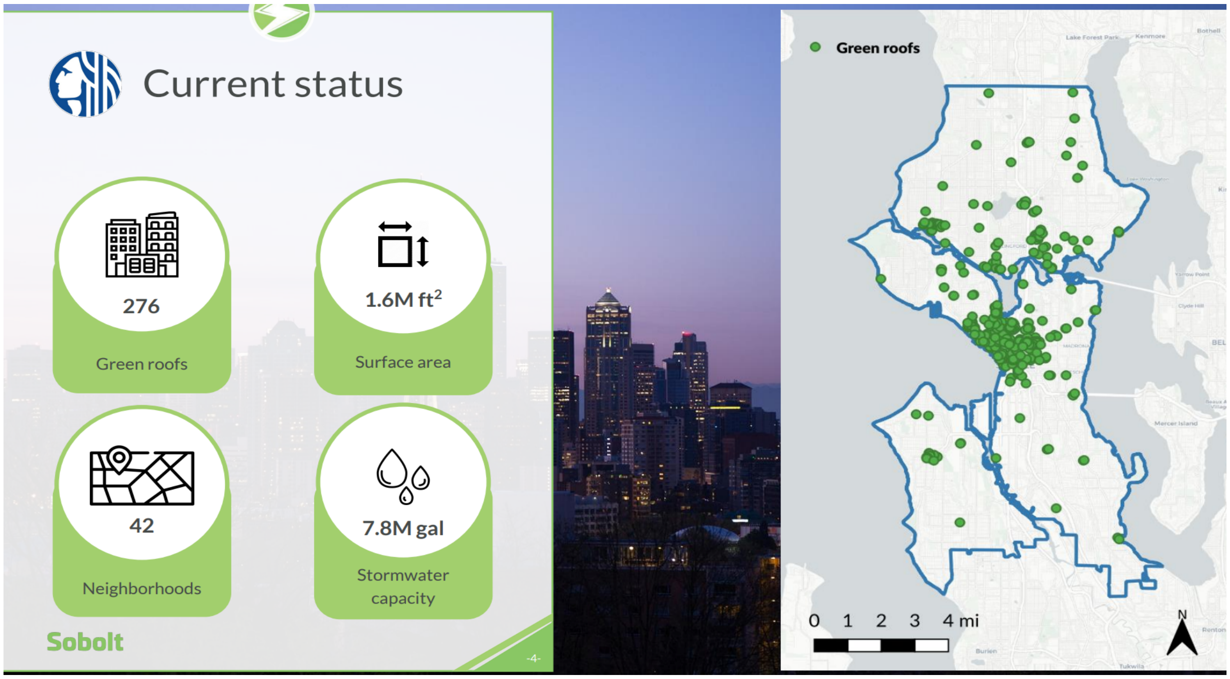
Once again, there is an overwhelming majority (more than 89%) of green roofs residing in urban centers/villages.

Steinberg (2018) briefly discussed carbon sequestration as a benefit of green roofs and cited a couple of literature sources including Getter et al.'s (2009) paper on green roof sequestration, but calculating sequestration was not part of this paper. Additionally, Steinberg (2018) did not categorize the green roofs in this paper. This GIS data is now lost, so it is not used in the current thesis.

In September 2019 [date inferred from GIS files given to City of Seattle], a firm named Sobolt analyzed estimated current and potential future green roofs in Seattle for Seattle Public Utilities and stormwater retention capacity. The firm used 2017 aerial imagery, 2016 LiDAR data for vegetation, and 2015 Seattle building outlines, in addition to their own database of green roof information; they then used two deep learning methods to estimate the location and size of current green roofs in Seattle. They initially found an estimate of 345 green roofs as of 2017, but then adjusted it to 276 due to a manual inspection based on initial low resolution, whereby they determined through this manual inspection that at least 80% of the original 345 green roofs were indeed present. Thus, their estimate was 276 green roofs, taking up ~1,600,000 square feet (Sobolt, n.d.). Their map is shown in Figure 14.

Figure 14

Sobolt's Seattle Green Roof Map and Infographic



Current status

276

Green roofs

1.6M ft²

Surface area

42

Neighborhoods

7.8M gal

Stormwater capacity

Sobolt

-4-

Note. From "Seattle Stormwater: Managing Urban Flooding from Above," by Caroprese, n.d. Sobolt. Copyright information unavailable/unclear. Reprinted with permission.

However, upon inspection, the GIS data did not seem to match up in either number or surface area of green roofs. The Sobolt staff member who created the analysis was not available for response. In reaching out to Seattle Public Utilities, staff member Dave LaClergue (2020) stated the following:

> When I did a reliability check on the data, I found that the layers captured most of the existing green roofs I know of, and identified many I didn't know about. Some of those were "false positives" where an internal courtyard registered as a green roof. The other problem I found was that the polygons were usually way off – they tended to count the whole rooftop even if only a small amount had vegetation. (personal communication)

Sobolt's (2019) work is the most recent work known to involve Seattle's green roofs. However, due to the aforementioned issues, this data is not used for the current thesis.

2.4: Influences of Urban Design on Carbon Sequestration of Green Roofs

Though green roofs are inherently urban design features, and both their design characteristics and their sequestration have been studied, there does not appear to be explicit discussion of 'urban design' or 'urban form' as an influence on carbon sequestration of green roofs. Various characteristics of green roofs impact carbon sequestration and other green roof functions: plant type, plant size, substrate type, substrate depth, location, etc. These are mentioned in Section *2.2.1* (for another review, see Shafique, Xue, et al., 2020). Most of these characteristics, in addition to maintenance routines, can be associated less with urban design than with horticulture or landscape design. Location is one characteristic that could be applicable in both a purely landscape context as well as a broader urban design context.

The green roofs analyzed in Getter et al.'s (2009) study were on top of a university building; no other specific locational information was given. Whittinghill et al.'s (2014) green roof platforms were designed in the same way as a previous study (VanWoert et al., 2005). It is thus inferred that the green roofs in this study were located 0.9 meters above the ground level, tilted slightly to increase sun exposure to the south. The height is noteworthy since building roofs are much taller, which could influence factors which affect sequestration. The green roof in Luo et al.'s (2015) study in Chengdu was located on a university building rooftop, and both general climatic information and broad urban goals were discussed to contextualize the location. Ondoño et al. (2016a, 2016b) used special tables for the green 'roofs' which were 0.2 meters tall and placed in a farm, and general climatic information was given. Collazo-Ortega et al. (2017)

studied a green roof on top of a building at a botanical garden, and a couple images providing some basic locational context were given, along with general climatic information. Heusinger & Weber (2017a) provided varied descriptions of the green roof studied, and reference another study by the same group (Heusinger & Weber (2017b), which provides even more detail and a photograph showing some visual context. The green roof was on top of an 18-meter parking garage near an airport, and this height was similar to other buildings in the area (Heusinger & Weber, 2017b). Heusinger & Weber (2017a) also considered airplane movement as well as general climatic and relatively specific weather information, in addition to vegetation features such as amount of coverage and a leaf area index (Heusinger & Weber, 2017a). Kuronuma & Watanabe's (2017) study took place at a particular university building, and it is inferred that the rooftop used is on the same building as where the plants were initially grown. General climatic information was given, though no direct details were given about the rooftop or its surroundings. Kuronuma et al.'s (2018) study took place at the same building, and it is inferred to be the same rooftop as in the 2017 experiment. Chen et al.'s (2018) experiment also took place at a university building, and the study was conducted on a building's roof. The building's roof was given as 28 meters, and general climatic information was described. Cai et al.'s (2019) study had a photograph and description of the built structure used for their green roof measurements. It can be inferred that this structure was on the ground, though the photograph shows a limited view of surroundings. The structure was 2.5 meters tall, with a green roof on top of part of it. Broad climatic and specific temperature information was also given.

Overall, there is a dearth of information from the green roof carbon sequestration studies on the surrounding environments. Some 'green roofs' were indeed on roofs, while others were closer to ground-level. Presumably, the green roofs would be located so as to have uninhibited access to light, though this is not certain. Heusinger & Weber (2017b) did indicate that the parking garage used was approximately the same height as other buildings in the area, and provided other environmental descriptions.

On a broader scale, exposure to green roofs and other forms of nature can potentially influence attitudes and decisions towards increasing greenspace in urban areas, as well as promote more sustainable behavior (Haksever, 2020; Zelenski et al., 2015).

Chapter 3: Methods

With the understanding gained thus far about how carbon sequestration works, its potential in green roofs, and how to account for green roofs in a city such as Seattle, the following methods are developed to map out the green roofs in Seattle with the most recently available data, and to estimate their carbon sequestration capacity using a collection of studies which have systematically analyzed green roof carbon sequestration.

The current study is the most detailed mapping of green roofs in Seattle yet for those areas of the city which are directly measured, and it is the first study to estimate the carbon sequestration capacity of green roofs in Seattle. Additionally, it is the first study to estimate carbon sequestration of green roofs at a city-wide scale using data from multiple studies, rather than estimating sequestration in general (George, 2013), or estimating potential sequestration in a given city or metropolitan area based on only that study alone (Cai et al., 2019; Chen et al., 2018; Collazo-Ortega et al., 2017; Getter et al. 2009; Luo et al., 2015).

It is important to organize the green roof carbon sequestration data and other previous information from the literature review in order to put it all into context and to utilize it for the subsequent analysis. Three considerations follow: climate considerations, defining the green roof vegetation intensity categories, and standardizing the sequestration rates from previous research so that they can be divided into groups in order to determine an average sequestration rate for each intensity category that will be used in this thesis. These three considerations are discussed in sections 3.1, 3.2, and 3.3, respectively. Attempting to integrate tree sequestration rates is then discussed in 3.4. Finally, mapping strategies will be described in 3.5.

3.1: Climate Considerations

Firstly, relevant data must be chosen; this is a challenge as there are no studies that take place in the same climate zone as Seattle. Based on the Köppen-Geiger climate classifications in Figure 7, the cities in which the green roof carbon sequestration studies discussed in Chapter 2 were performed are in the climate classification areas shown in Table 1, shown along with Seattle:

Table 1

Köppen-Geiger Climate Classifications of Cities with Green Roof Carbon Sequestration Data, and Seattle

City	Köppen-Geiger climate class	Climate Description
East Lansing, Michigan, USA	Dfa	‘cold, without dry season, hot summer’
Chengdu, China	Cwa	‘temperate, dry winter, hot summer’
Murcia, Spain	BSh/BSk	‘arid, steppe, hot/cold’
(southern) Mexico City	Cwb	‘temperate, dry winter, warm summer’
Berlin, Germany	Cfb (Cfa at this site on this year)	‘temperate, without dry season, warm/hot summer’
Chiba, Japan	Cfa	‘temperate, without dry season, hot summer’
Nanjing, China	Cfa	‘temperate, without dry season, hot summer’
Wuxi, China	Cfa	‘temperate, without dry season, hot summer’
Seattle, Washington, USA	Csb	‘temperate, dry summer, warm summer’

Note. Data in this table is based on information from Beck et al., 2018; Climate-data.org, n.d.; and Agencia Estatal de Meteorología, n.d.

Seattle’s climate is classified as Csb (‘temperate, dry summer, warm summer’), meaning it is the only city here that is/has all of the following simultaneously: non-arid, dry summer, temperate, and warm but not hot summer (Beck et al., 2018). It is the only city here with the official designation of having a dry summer. Technically Murcia, Spain also fits the qualifications for a dry summer, but it is not categorized that way because of its arid climate overall. Seattle gets significantly more precipitation than Murcia, Spain, but still has a relatively dry summer while the other cities do not. This combination of winter rain and summer dryness can have a significant impact on vegetation, which in turn can have implications for carbon sequestration. Based on data and insights from Smith & Smith (2015) and McPherson et al. (2016), the cities in Table 1 with temperate temperatures, without a dry season, and warm or hot summers would presumably have the highest sequestration rates within the set of cities, unless the rain precluded enough sunshine or the heat was excessive for optimal plant growth. Nevertheless, this is the data available for green roof studies, so these differences are acceptable with the understanding that growing those same plants in Seattle (if possible) would almost certainly have different results.

3.2: Defining Extensive, Semi-Intensive, and Intensive Green Roofs

Secondly, extensive, semi-intensive, and intensive characteristics must be defined for this study, so that the green roof sequestration studies above can be allocated to the proper category. As Berndtsson (2010) states in their green roof review, green roofs with depths of 11-15 cm are considered either extensive or intensive by different authors. This concurs with a book review by Pérez & Perini (2018), which states extensive as having 6 - 20 cm soil depth, while semi-intensive have 10 - 25 cm soil depth, and intensive have greater than 25 cm soil depth. The authors in the sequestration review earlier in this thesis have stated differing definitions on their own and citing research- most state that extensive green roofs are less than 15 cm, while intensive are more than 15 cm, while two papers with the same lead author state extensive roofs are less than 20 cm and intensive are more than 20 cm (FLL, 2002; FLL, 2008; Getter et al. 2009; Heusinger & Weber, 2017; Kuronuma & Watanabe, 2017; Kuronuma et al., 2018; Ondoño, Martínez-Sánchez, & Moreno, 2016a; Shafique, Xue, et al., 2020). It must also be considered that almost all of the studies on green roof carbon sequestration are in extensive green roofs; there is limited data for what would be deemed as semi-intensive or intensive green roofs. Examining the Seattle Green Factor's most up-to-date point system for green roof soil depth provides a guide for decision-making. The first category is between 2 and 4 inches (5.08 cm to 10.16 cm). The second category is between 4 inches and 8 inches (10.16 cm and 20.32 cm). The third category is more than 8 inches (20.32 cm). This guidance can be a proxy for extensive, semi-intensive, and intensive, which generally fits the descriptions above, and also allows for more than one study to be used for semi-intensive (Whittinghill et al., 2014, in which the carbon sequestration levels were already higher than usual for extensive green roofs, despite them being labeled extensive). We can simplify and say:

Extensive: 5.1 cm to 10.2 cm

Semi-Intensive: 10.2 cm 20.3 cm

Intensive: 20.3 cm and above

These categories are used in section 3.3 to divide the previous research based on the soil depths used in those studies, and apply their sequestration rates to the intensity categories created above.

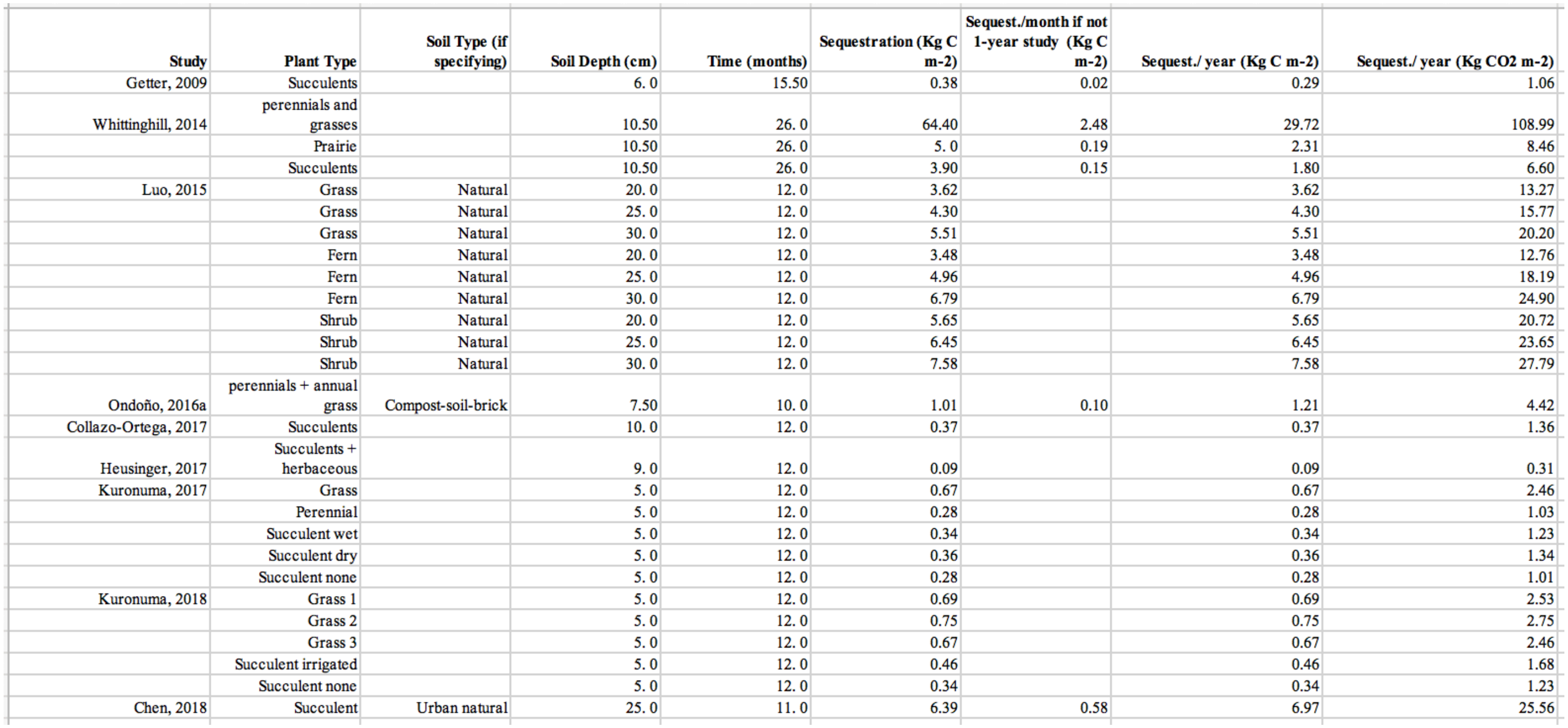
As is explored further in section 3.5 (Mapping Strategies), the vegetation in Seattle is actually not categorized based on soil depth. This is simply because aerial and satellite imagery cannot provide conclusive soil depth measurements. Thus, approximate vegetation size is used as a proxy for intensity, as it is assumed that larger vegetation are likely located in deeper soil.

3.3: Standardizing Green Roof Carbon Sequestration Rates from Previous Research

Thirdly, the data from the studies must be standardized and normalized for easy interpretation. Studies report on carbon sequestration ability over different periods of time, and some report on kg C m^{-2} per period of time while others report kg CO_2 m^{-2} per period of time. Here the data is standardized to kg CO_2 m^{-2} per year.

Table 2

Summary and Standardization of Green Roof Sequestration Rates Being Included for Seattle Estimates



Study	Plant Type	Soil Type (if specifying)	Soil Depth (cm)	Time (months)	Sequestration (Kg C m-2)	Sequest./month if not 1-year study (Kg C m-2)	Sequest./ year (Kg C m-2)	Sequest./ year (Kg CO2 m-2)
Getter, 2009	Succulents		6. 0	15.50	0.38	0.02	0.29	1.06
Whittinghill, 2014	perennials and grasses		10.50	26. 0	64.40	2.48	29.72	108.99
	Prairie		10.50	26. 0	5. 0	0.19	2.31	8.46
	Succulents		10.50	26. 0	3.90	0.15	1.80	6.60
Luo, 2015	Grass	Natural	20. 0	12. 0	3.62		3.62	13.27
	Grass	Natural	25. 0	12. 0	4.30		4.30	15.77
	Grass	Natural	30. 0	12. 0	5.51		5.51	20.20
	Fern	Natural	20. 0	12. 0	3.48		3.48	12.76
	Fern	Natural	25. 0	12. 0	4.96		4.96	18.19
	Fern	Natural	30. 0	12. 0	6.79		6.79	24.90
	Shrub	Natural	20. 0	12. 0	5.65		5.65	20.72
	Shrub	Natural	25. 0	12. 0	6.45		6.45	23.65
	Shrub	Natural	30. 0	12. 0	7.58		7.58	27.79
Ondoño, 2016a	perennials + annual grass	Compost-soil-brick	7.50	10. 0	1.01	0.10	1.21	4.42
Collazo-Ortega, 2017	Succulents		10. 0	12. 0	0.37		0.37	1.36
Heusinger, 2017	Succulents + herbaceous		9. 0	12. 0	0.09		0.09	0.31
Kuronuma, 2017	Grass		5. 0	12. 0	0.67		0.67	2.46
	Perennial		5. 0	12. 0	0.28		0.28	1.03
	Succulent wet		5. 0	12. 0	0.34		0.34	1.23
	Succulent dry		5. 0	12. 0	0.36		0.36	1.34
	Succulent none		5. 0	12. 0	0.28		0.28	1.01
Kuronuma, 2018	Grass 1		5. 0	12. 0	0.69		0.69	2.53
	Grass 2		5. 0	12. 0	0.75		0.75	2.75
	Grass 3		5. 0	12. 0	0.67		0.67	2.46
	Succulent irrigated		5. 0	12. 0	0.46		0.46	1.68
	Succulent none		5. 0	12. 0	0.34		0.34	1.23
Chen, 2018	Succulent	Urban natural	25. 0	11. 0	6.39	0.58	6.97	25.56

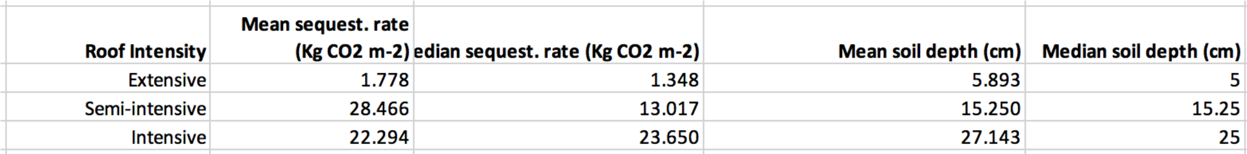
Note. To standardize sequestration into an annual rate for studies which were not one year in length, the sequestration rate for those studies' lengths (e.g., sequestration over a 10-month study) were converted into a sequestration rate per month. That rate was then multiplied by 12. When needed, kg C m^{-2} were multiplied by 3.66666666.

Table 2 takes the green roof studies' data which generally have sufficient information to be included in this current carbon sequestration study (one study does not count belowground biomass), and normalizes it all into kilograms of carbon dioxide per square meter per year. Green roof study results have been typically excluded if their experimental method or materials would likely be uncommon in Seattle's extant green roofs (for example, the sludge and biochar-containing soils in Luo et al.'s (2015) study).

Next, the included studies are combined within their respective intensity categories to determine the average carbon sequestration rate for the extensive, semi-intensive, and intensive categories, based on the framework of soil depth described above. The average soil depth is also shown for consideration:

Table 3

Average Sequestration Rates and Soil Depths of the Green Roof Typologies



Roof Intensity	Mean sequest. rate (Kg CO2 m-2)	edian sequest. rate (Kg CO2 m-2)	Mean soil depth (cm)	Median soil depth (cm)
Extensive	1.778	1.348	5.893	5
Semi-intensive	28.466	13.017	15.250	15.25
Intensive	22.294	23.650	27.143	25

It is clear that the mean sequestration rate is very skewed for the semi-intensive green roof category. Thus, the calculations for estimating Seattle's carbon sequestration in this thesis are performed with the median sequestration rate.

3.4: Determining Useful Sequestration Rates of Trees Deemed Infeasible

Before finalizing these sequestration rates, the sequestration capacity of trees should ideally be included and integrated into the Intensive category's sequestration rate. Two approaches are attempted to integrate tree sequestration data; however, these approaches do not provide workable results. There are numerous reasons for this, but one surprise is the low sequestration rates found. Similarly, Nowak et al.'s (2013) study on urban and community trees in the U.S. showed that Washington state as a whole had a net sequestration rate of 0.701 kg CO_2 m^{-2} per year, which is less than half the sequestration rate of the median Extensive green roof sequestration rate in Table 3. Even some of the most heavily forested areas in Oregon had a Net Primary Productivity of approximately 3 kg CO_2 per year (and less than 0.75 kg CO_2 per year when considering Net Ecosystem Productivity). There is perhaps a methodological or systematic difference causing these surprising results. The attempted strategies to determine carbon sequestration rates for trees in Seattle are described in the Appendix to demonstrate the challenges of attaining accurate and useful sequestration rates for (elevated/rooftop) trees in Seattle. The measurement methods in the green roof studies seemed generally reliable, and there also is not data directly involving rooftop trees, either, so the decision was made to only use the calculations from the chosen sections of green roof studies.

3.5: Mapping Strategies

Due to difficulty in obtaining previous or accurate GIS data files accounting green roofs in Seattle, this work was re-done in this study with a new method.

An automated, remote analysis method similar to Sobolt's (n.d.) was considered; however, satellite or aerial imagery with a high enough resolution was not found to be available in a financially feasible way; the aerial imagery used in this thesis is the highest resolution able to be utilized, but was in a base map format which seemed unable to allow remote analysis. Thus, the city of Seattle was visually scanned for building vegetation, and the various building vegetations were manually drawn out in close detail.

There were numerous data used for visually scanning Seattle's buildings. One was the same visual layer that the green roofs were drawn onto: the 2019 aerial imagery through the King County GIS Center, via the base map itself as well as a version on King County iMap (King County/Aerials Express, n.d; King County GIS Maps, n.d.). Another main data source used was Google Maps, particularly the satellite imagery and its 3-D visualization option (which showed buildings in approximately 2019 through much of this thesis's mapping process, and then updated to more recent 3-D visualizations (showing buildings in approximately the second half of 2020) later on in this thesis's mapping process (likely at the point when the author was mapping the South Lake Union area)). Google Maps was also used for its 'Street View' option and user-uploaded photographs (Google, 2021). Google Earth was also used; unlike Google Maps, Google Earth allowed examination of particular elevation changes to determine if courtyards were elevated when indeterminate otherwise, as well as certain plants in order to assist in categorization (Google, n.d.). Also, in addition to King County iMap's aerial imagery from 2019, aerial imagery from earlier years (e.g., 2017, 2015, 2013) was used to help in determining site/building and vegetation details which were sometimes difficult to determine with other tools (King County/Aerials Express, n.d.). The King County Department of Assessments website was sometimes accessed through King County iMap for it often showed street-level site imagery which helped determine if attached buildings were considered separate or as one, for the sake of recording how many buildings had green roofs/elevated courtyards (King County Department of Assessments, 2019). Lastly, personal photographs of buildings were occasionally utilized to help in identifying the size of vegetation.

King County's 2019 imagery was, before Google Maps' update, generally shown as slightly more recent than the Google Maps satellite imagery- projects shown as under construction in Google Maps were further along or completed in the King County imagery. Google Maps satellite imagery was an easier tool for visually scanning the city, while the King County aerial imagery was used in ArcGIS/ArcMap as the base map upon which the green roof details were confirmed or clarified and green roof polygons were drawn (Google Maps, 2021; King County/Aerials Express, n.d.). Google Maps 3-D visualization was often used to elucidate the type of building vegetation by providing an approximate visualization of vegetation height. As mentioned, Google Earth could be used to numerically determine the height of a building, though the two platforms did appear to have the same imagery (Google Earth, 2021; Google Maps, n.d.).

The mapping software for drawing the green roofs and elevated courtyards was ArcGIS Desktop Version 10.7.1 (Esri, 2019). Within ArcMap, the data frame coordinate system was labeled as WGS_1984_Web_Mercator_Auxiliary_Sphere, and the data frame projection was labeled as Mercator_Auxiliary_Sphere. The King County base map had the same coordinate system/projection, and the geographic coordinate system was labeled as GCS_WGS_1984. Each green roof shapefile created had a projected coordinate system of NAD_1983_HARN_StatePlane_Washington_North_FIPS_4601_Feet, while the projection was Lambert_Conformal_Conic, and the geographic coordinate system was GCS_North_American_1983_HARN. Originally, the shapefile projection/projected coordinate system were designed to match the base map; however, when checking the accuracy of area measurements against King County iMap's 2019 Aerial Imagery on its own website, there were major discrepancies (King County/Aerials Express, n.d.). In communicating with a GIS analyst/spatial services staff member in the King County GIS Center, it was stated to use the projected coordinate system of NAD_1983_HARN_StatePlane_Washington_North_FIPS_4601 for the new shapefiles; even though the imagery is shown as being in a Web Mercator projection, it was stated that the actual data is in the State Plane projection (Carpenter, 2020, personal communication). Checking the accuracy of area measurements against King County iMap with the State Plane projection in ArcMap showed accurate measurements, so the analysis proceeded as such.

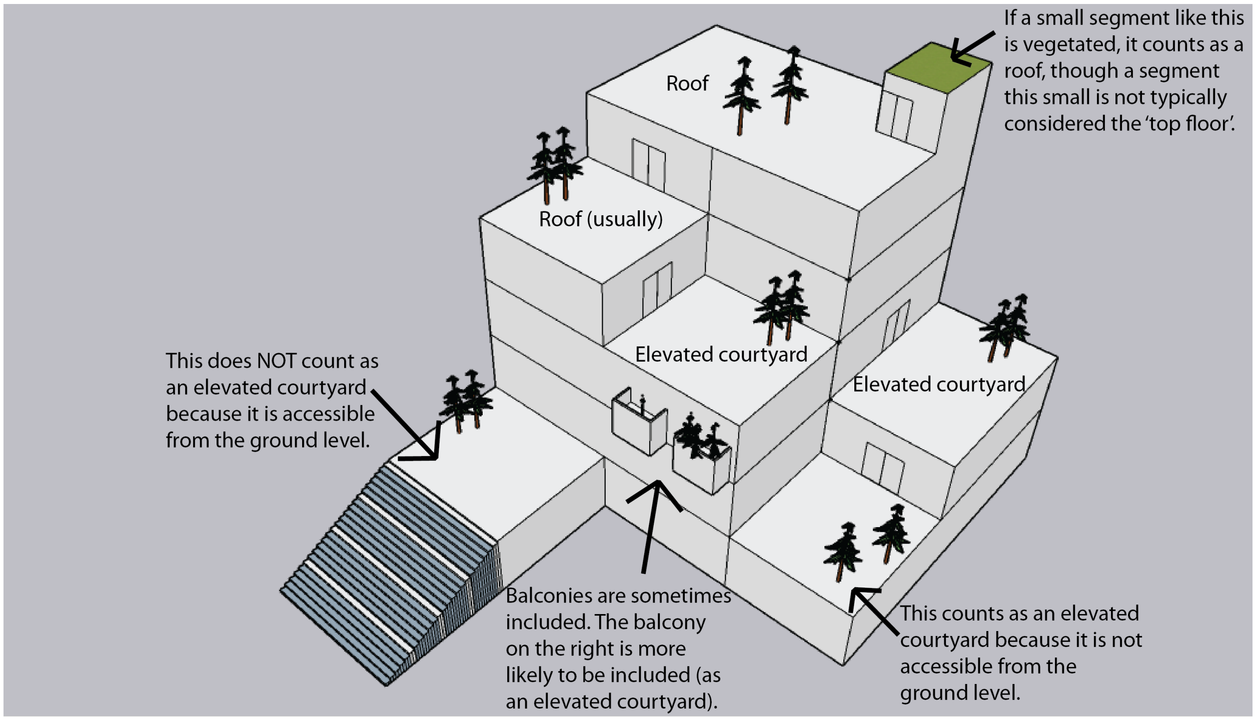
Land use and neighborhood data is found through the City of Seattle databases (Seattle Geodata, 2020; Seattle Open Data Portal, 2021).

In determining what areas to mark as green roofs, a plethora of considerations emerge. Firstly, decisions must be made about how to categorize the green roofs. Originally, the plan was to categorize the green roofs into three categories: extensive green roof, semi-intensive green roof, and intensive green roof. However, it soon became clear that these would not capture the totality of elevated building vegetation; indeed, the great variety of building designs and upper-level setbacks blur what is even considered to be a rooftop. As with Steinberg's (2018) green roof analysis, it makes sense to include vegetation that is on the building footprint but elevated above ground level. Ground-level vegetation on the parcel is not relevant to the topic, and green walls are not included. Green roofs were the initial idea and emphasis but it became clear that there were many areas high up on buildings that had substantial vegetation and it would seem incomplete to ignore these sections of vegetation. At the same time, to equate all elevated building vegetation as green roofs seems inaccurate. Thus, three new categories have been added: extensive elevated green courtyard, semi-intensive elevated green courtyard, and intensive elevated green courtyard. However, even these categories could be challenged due to topographical conditions near the ground level. The framework is created such that elevated courtyards could generally not be accessible from the street level to be considered an elevated courtyard. It has become clear over time that considerations must ultimately be given to building-specific and site-specific characteristics, though an attempt is made to be consistent. The topic of deciding if a courtyard is deemed ‘elevated’ or not is discussed in more detail and with examples in Chapter 4 (the Results).

Figure X illustrates a generic building with vegetation on multiple levels, describing how those levels would be categorized in this mapping process.

Figure 15

Typical Classifications for Different Levels of Elevated Vegetation



Note. The trees and the flat grass area are simply examples of vegetation to aid in illustration. Figure created by author using SketchUp Pro 2020 (Copyright by Trimble, 2017/2020).

In addition to making judgments on whether part or none of an elevated courtyard should be considered, there are also judgments on whether a portion of elevated vegetation is considered a roof or an elevated courtyard. Vegetation level is always considered to be a green roof if it is on the top level of a building. It would also be considered a green roof if it is on the floor below the top level, and often but not always two floors below the top level, depending on building-specific designs and functionality of the vegetative level- a more surrounded courtyard-like design, for example, would likely elicit an elevated courtyard demarcation. Below that would generally be considered an elevated courtyard. More considerations occurring throughout the mapping process are discussed in more detail in Chapter 4 (the Results).

In terms of classifying extensive vs. semi-intensive vs. intensive vegetation, since there is not readily available data on soil depth or species for the vegetated locations, a subjective judgment has to be made based on the aerial images and satellite visualizations in order to make a determination, typically via observing the vegetation since soil depth can only sometimes be approximated (such as in pots, which themselves are not perfect indicators as vegetation size does not always correlate strongly with pot depth).

Regarding the general classification of vegetation intensity between extensive, semi-intensive, and intensive, Figures 3-6 provide visual examples and descriptions which serve as useful models for making determinations. There are instances when it can be difficult to choose between one intensity category or another, because the vegetation could potentially fit into either category based on the size/height. In order to make judgments on vegetation intensity, the vegetative forms are examined in a variety of ways: from a 2-D perspective on King County's aerial imagery, from a 3-D perspective using Google Earth's 3-D feature, from the street using the 'street view' feature, and sometimes from user-uploaded photographs when available for areas in which vegetation is challenging to categorize otherwise. When looking from a 2-D perspective, the size of shadows being cast could indicate the height of vegetation and to which category it should belong. As for the 2-D perspective of the vegetation itself, if it is clearly flat, nearly flat, or slightly raised, it is likely classified as Extensive. Intensive is chosen when foliage or crown-like features were clearly visible, especially when large shadows are cast. Semi-intensive is at an intermediate height/thickness (a shadow is usually present).

There are several miscellaneous considerations in effect during the mapping. Significant effort went into avoiding or removing utility boxes, walking paths, and similar non-vegetative objects in the middle of larger vegetative spaces, so as not to overestimate the vegetation. Artificial turf is common, and this is specifically avoided whenever identified. Balconies are not usually included unless there were, subjectively, significant amounts of vegetation visible on them. Sequestration rates are assumed to be the same for elevated courtyards as for green roofs. Regarding the counting of buildings, it is decided that connected buildings are usually considered as one building. Sometimes this consideration comes up with larger buildings that are or seem to be not just adjacent but connected to each other. A smaller example of this is rowhouses- if there is a set of 3 rowhouses connected to each other with green roofs on 2 or 3 of them, this is counted as 1 building.

Lastly, in the situation that arises in which not all green roofs and elevated green courtyards are manually counted, there is a method to estimate their density in unaccounted areas. Land uses are composed of particular types of built structures, intensities, and uses. When direct observations and manual recordings of green roofs and elevated green courtyards occur over a significant portion of the city, their density in particular land uses can be used to approximate the density in the same land use categories elsewhere in the city.

The portion of the city which is directly and completely observed in this thesis is first overlaid on neighborhood areas defined by a City of Seattle map, with manual additions and subtractions performed to increase an otherwise accurate overlay (Seattle Geodata, 2020). Then, the land uses corresponding with the observed areas are added using another City of Seattle map (Seattle Open Data Portal, 2021). The square footage of each type of green roof and elevated green courtyard in each type of land use is divided by the square footage of each type of land use within the 'accounted for' area of the city. Then the proportion of greenspace area in each land use area is multiplied by the area of each land use in the 'unaccounted for' areas of the city, with the assumption that the same type of land use will have the same proportion of green roofs and elevated green courtyards throughout the city. The accounted green roof/elevated green courtyard areas combined with the unaccounted/estimated green roof and elevated green courtyard areas to determine the total estimated green roof and elevated green courtyard square footage for the entire city. The estimated carbon sequestration of green roofs and elevated green courtyards in Seattle follow this information. Regarding accounted and unaccounted areas, it is noteworthy that there is also a portion of the city that is partially accounted, where large buildings were examined for green roofs and elevated green courtyards. For the sake of the land uses analyses, this area was joined with the unaccounted area. Maps showing the accounted, partially accounted, and unaccounted areas of the city are shown in Chapter 4.

Using neighborhood and land use maps also provide an opportunity to organize the prevalence of green roofs and elevated green courtyards within these boundaries. One example is directly recording the area of each type of green roof and elevated green courtyard in each neighborhood within the fully accounted area. Then, each neighborhood which is not fully accounted is divided up into each type of land use therein, and the same proportions used above (of area of each type of green roof and elevated green courtyard to area of each type of land use) are multiplied by the area of each type of land use in each of the unaccounted neighborhoods in order to estimate the amount of each type of green roof and elevated green courtyard in each neighborhood.

Chapter 4: Results

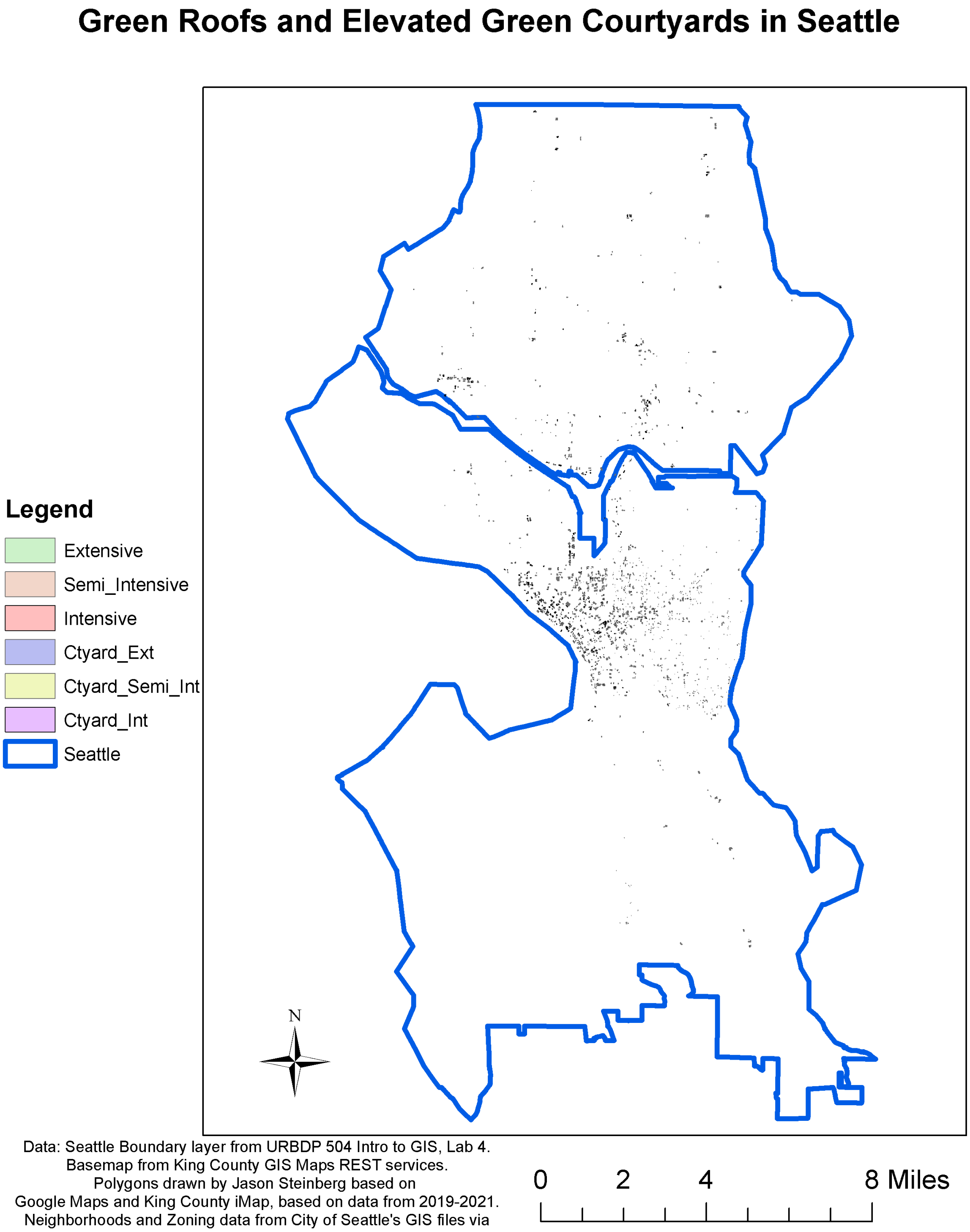
These results discuss the quantitative results found from the mapping process. Then qualitative reflections discuss detailed strategies learned and integrated during the mapping process, caveats, qualifications, examples, and occurrences which occurred during the mapping process which impacted mapping strategies.

4.1: Quantitative Results

Of those directly observed and recorded, there are 1,527 known buildings with green roofs and/or elevated green courtyards within the city of Seattle. There are 631 with Extensive roofs, 769 with Semi-Intensive roofs, 739 with Intensive roofs, 216 with Extensive elevated courtyards, 378 with Semi-Intensive elevated courtyards, and 515 with Intensive elevated courtyards. Figures X-X visualize these green roofs and green elevated courtyards.

Figure 16

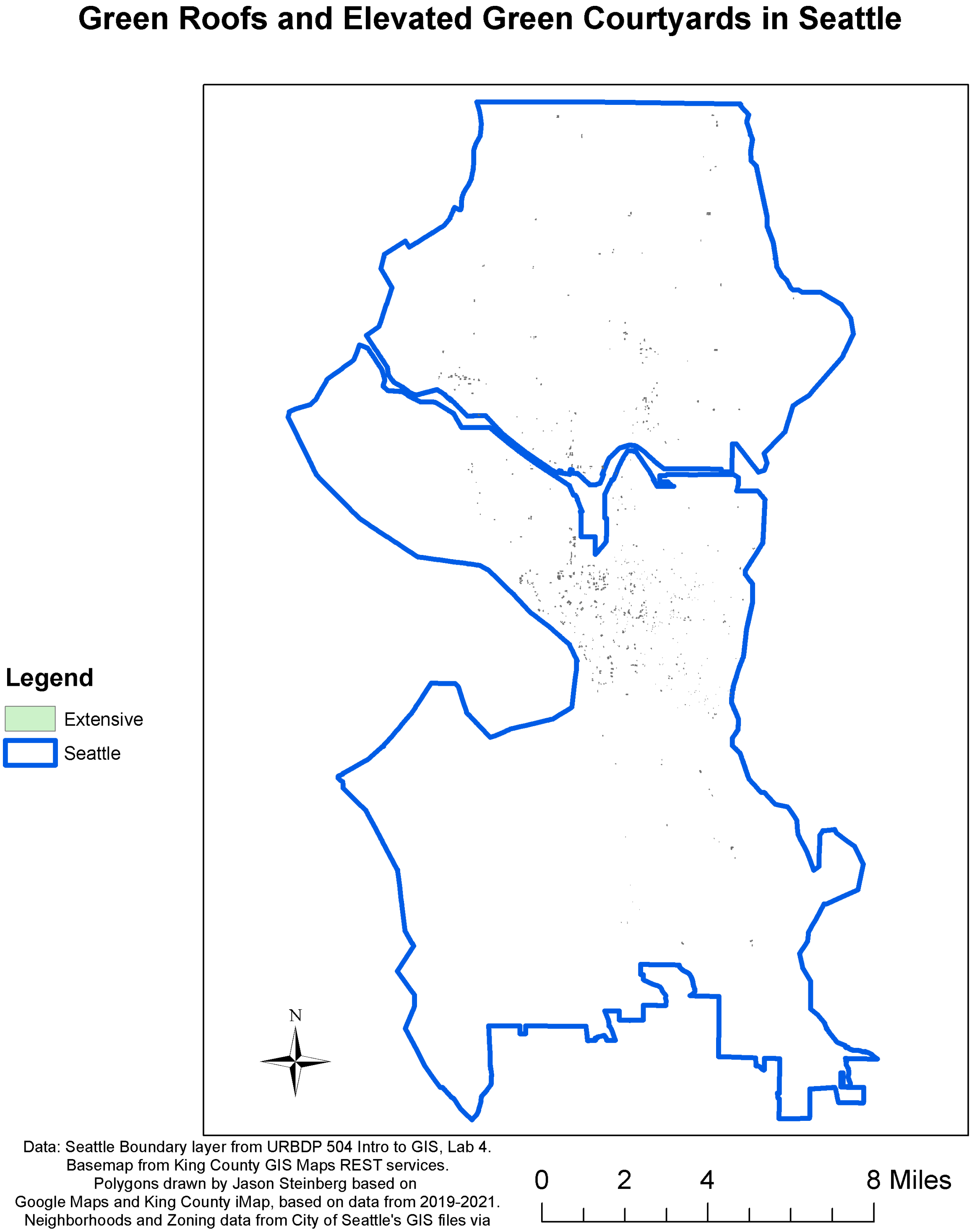
Map of All Green Roofs and Elevated Green Courtyards Found and Visualized in this Study



Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4.
Basemap from King County GIS Maps REST services.
Polygons drawn by Jason Steinberg based on
Google Maps and King County iMap, based on data from 2019-2021.
Neighborhoods and Zoning data from City of Seattle's GIS files via
Seattle GeoData and Seattle Open Data.

Figure 17

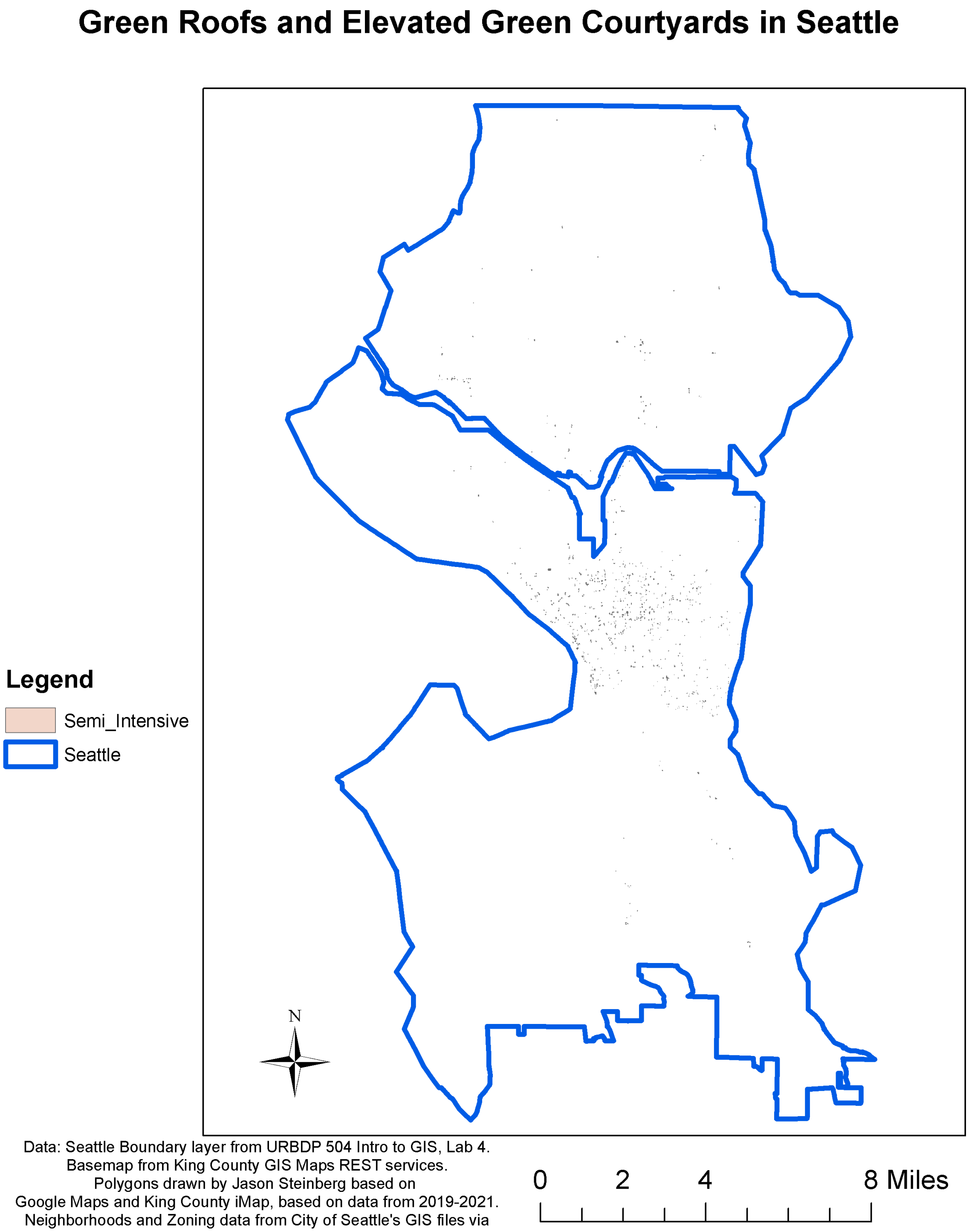
Map of Extensive Green Roofs in Seattle



Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4.
Basemap from King County GIS Maps REST services.
Polygons drawn by Jason Steinberg based on
Google Maps and King County iMap, based on data from 2019-2021.
Neighborhoods and Zoning data from City of Seattle's GIS files via
Seattle GeoData and Seattle Open Data.

Figure 18

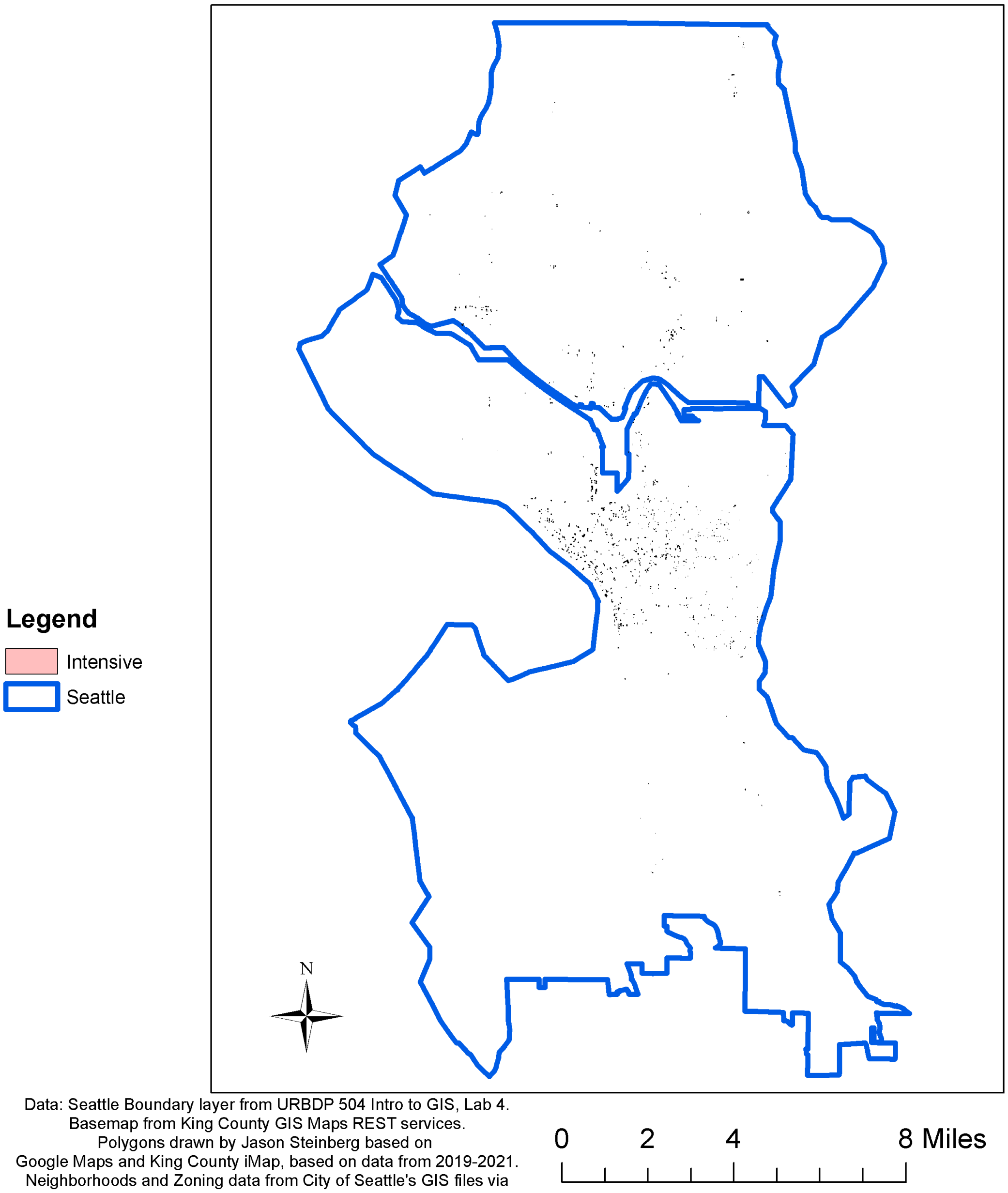
Map of Semi-Intensive Green Roofs in Seattle



Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4.
Basemap from King County GIS Maps REST services.
Polygons drawn by Jason Steinberg based on
Google Maps and King County iMap, based on data from 2019-2021.
Neighborhoods and Zoning data from City of Seattle's GIS files via
Seattle GeoData and Seattle Open Data.

Figure 19

Map of Intensive Green Roofs in Seattle

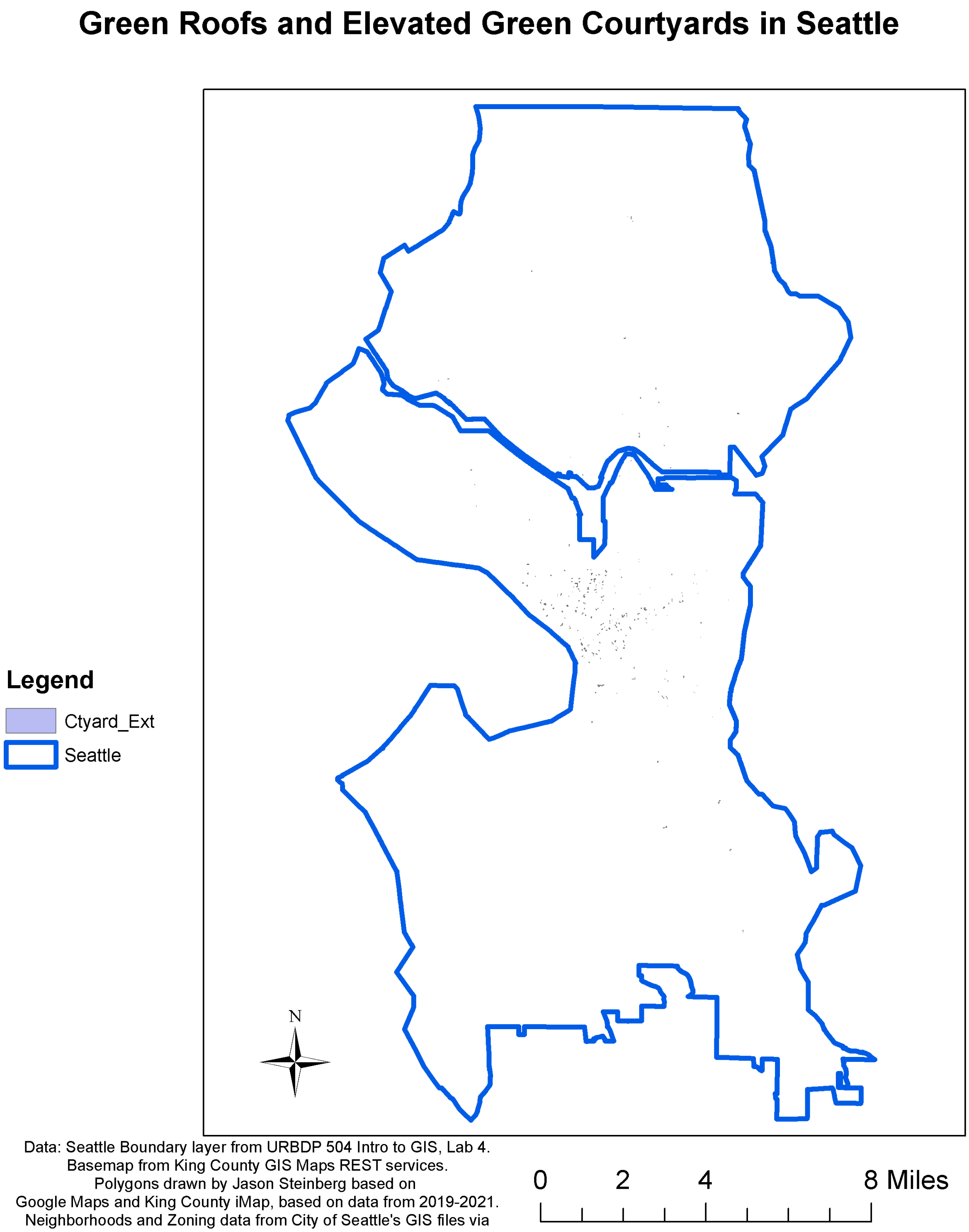


Green Roofs and Elevated Green Courtyards in Seattle

Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4.
Basemap from King County GIS Maps REST services.
Polygons drawn by Jason Steinberg based on
Google Maps and King County iMap, based on data from 2019-2021.
Neighborhoods and Zoning data from City of Seattle's GIS files via
Seattle GeoData and Seattle Open Data.

Figure 20

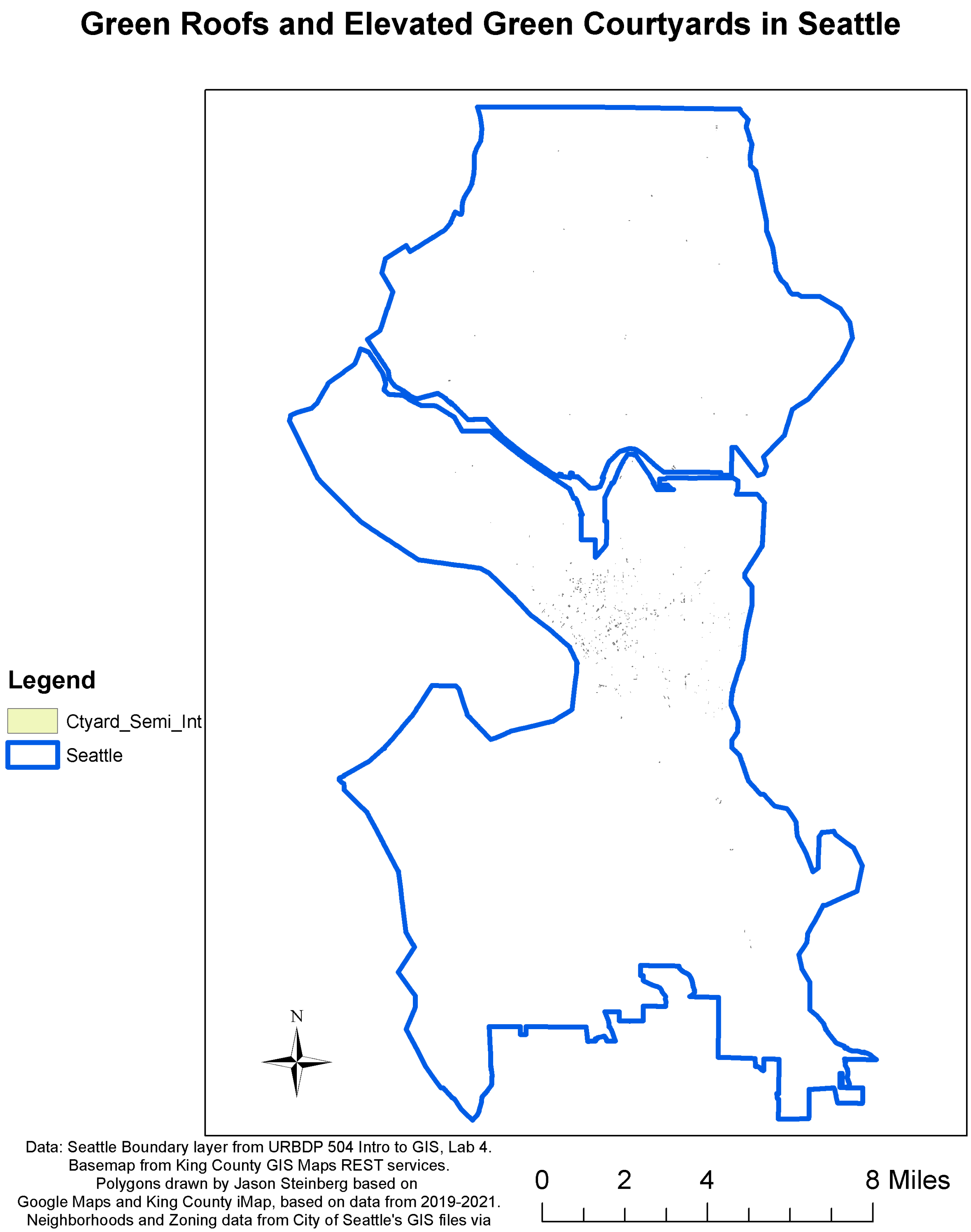
Map of Extensive Elevated Green Courtyards in Seattle



Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4.
Basemap from King County GIS Maps REST services.
Polygons drawn by Jason Steinberg based on
Google Maps and King County iMap, based on data from 2019-2021.
Neighborhoods and Zoning data from City of Seattle's GIS files via
Seattle GeoData and Seattle Open Data.

Figure 21

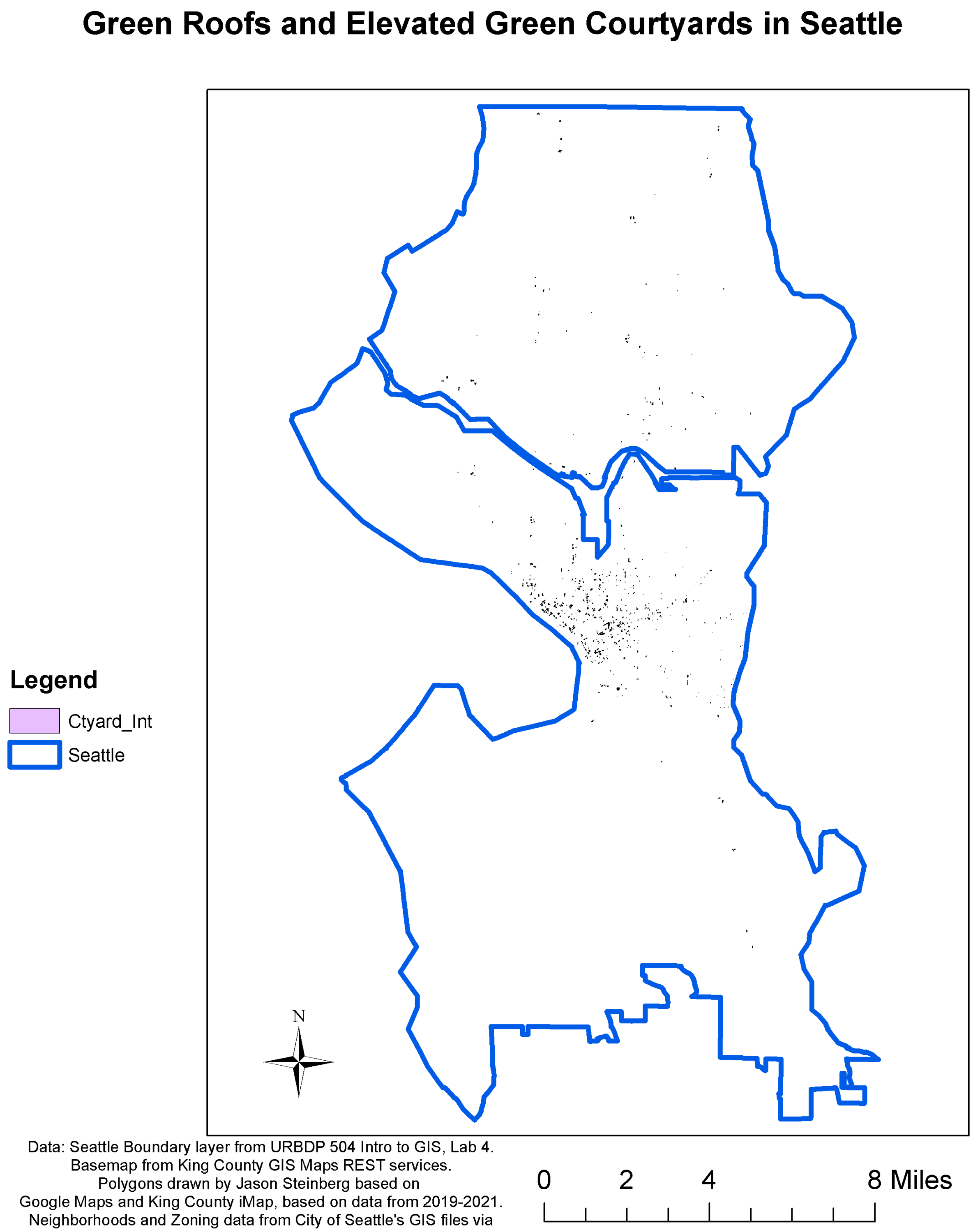
Map of Semi-Intensive Elevated Green Courtyards in Seattle



Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4.
Basemap from King County GIS Maps REST services.
Polygons drawn by Jason Steinberg based on
Google Maps and King County iMap, based on data from 2019-2021.
Neighborhoods and Zoning data from City of Seattle's GIS files via
Seattle GeoData and Seattle Open Data.

Figure 22

Map of Intensive Elevated Green Courtyards in Seattle



Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4.
Basemap from King County GIS Maps REST services.
Polygons drawn by Jason Steinberg based on
Google Maps and King County iMap, based on data from 2019-2021.
Neighborhoods and Zoning data from City of Seattle's GIS files via
Seattle GeoData and Seattle Open Data.

Table 4

Descriptive Statistics on Accounted Green Roofs

Roof type	Number of buildings	Min size (sq. ft.)	Max size (sq. ft.)	Mean size (sq. ft.)	Total area (sq. ft.)
Extensive green roof	631	0.57	56,783.63	1,885.26	1,189,601.76
Semi-intensive green roof	769	0.48	19,315.47	181.84	139,833.97
Intensive green roof	739	0.65	12,343.66	275.41	203,531.36
Green roof total sq. ft.					***1,532,967.09***
Extensive elev. green courtyard	216	0.43	7,362.75	764.79	165,194.54
Semi-intensive elev. green courtyard	378	0.78	4,186.42	253.37	95,775.05
Intensive elev. green courtyard	515	0.32	27,688.41	811.05	417,688.40
Elev. green courtyard total sq. ft.					***678,657.99***
Combined total sq. ft.					**2,211,625.08**

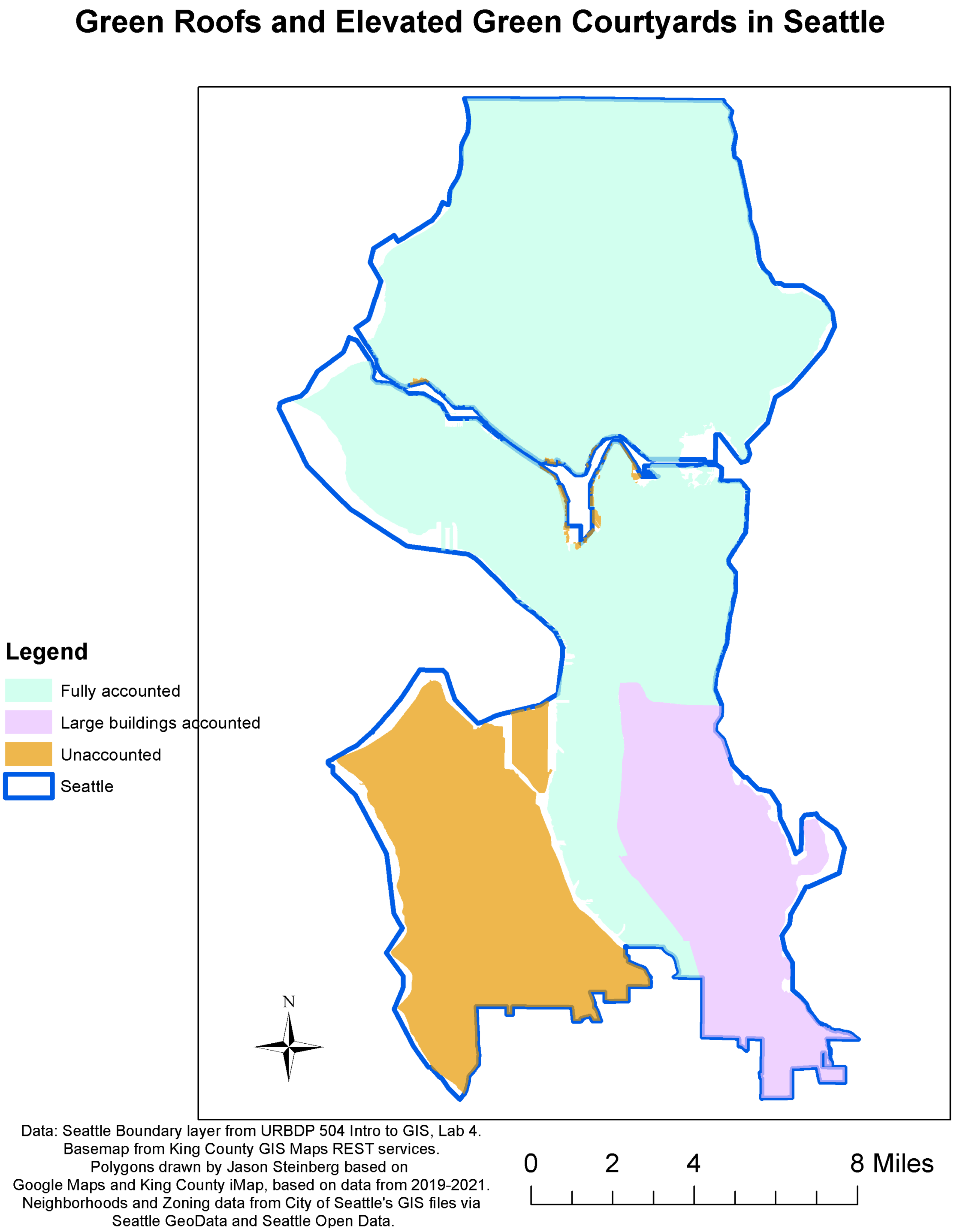
Note. There can be multiple types of green roofs and elevated green courtyards on one building.

As shown in Table 4, there is a total of 2,211,625 square feet of green roofs and elevated green courtyard space that has been accounted for in Seattle. Considering the median sequestration rates for green roofs/elevated green courtyards of different intensities, the total CO_2 sequestered among accounted vegetation is 1,819.52 metric tons.

However, this does not constitute all of the green roofs and elevated green courtyards in Seattle. Due to logistics, the entirety of Seattle's green roofs and elevated green courtyards are not mapped. Figures 23-26 show the areas of the city fully accounted for, partially accounted for, and not at all accounted for, in addition to related neighborhood visualizations.

Figure 23

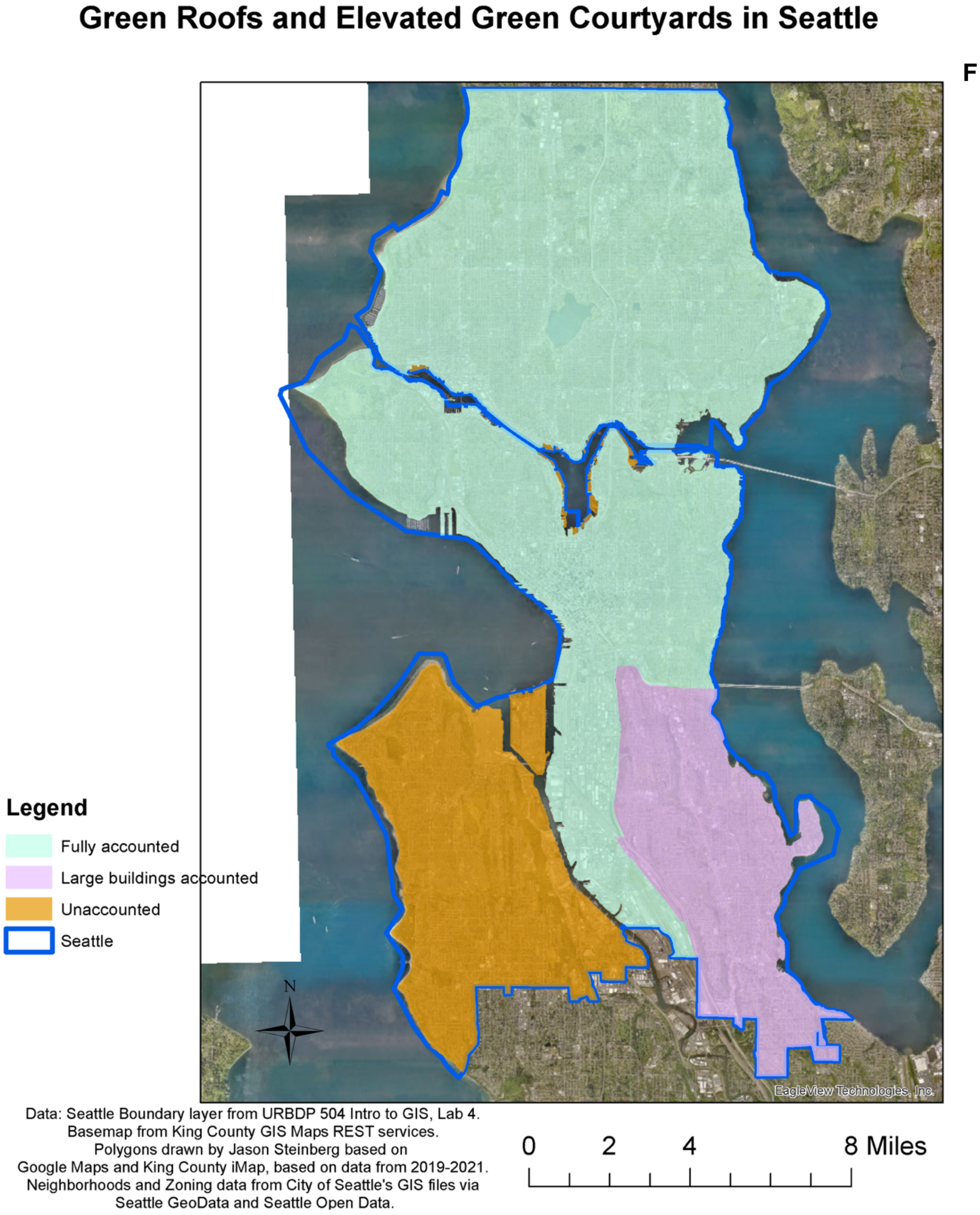
Accounted, Partially Accounted, and Unaccounted Areas in Seattle



Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4.
Basemap from King County GIS Maps REST services.
Polygons drawn by Jason Steinberg based on
Google Maps and King County iMap, based on data from 2019-2021.
Neighborhoods and Zoning data from City of Seattle's GIS files via
Seattle GeoData and Seattle Open Data.

Figure 24

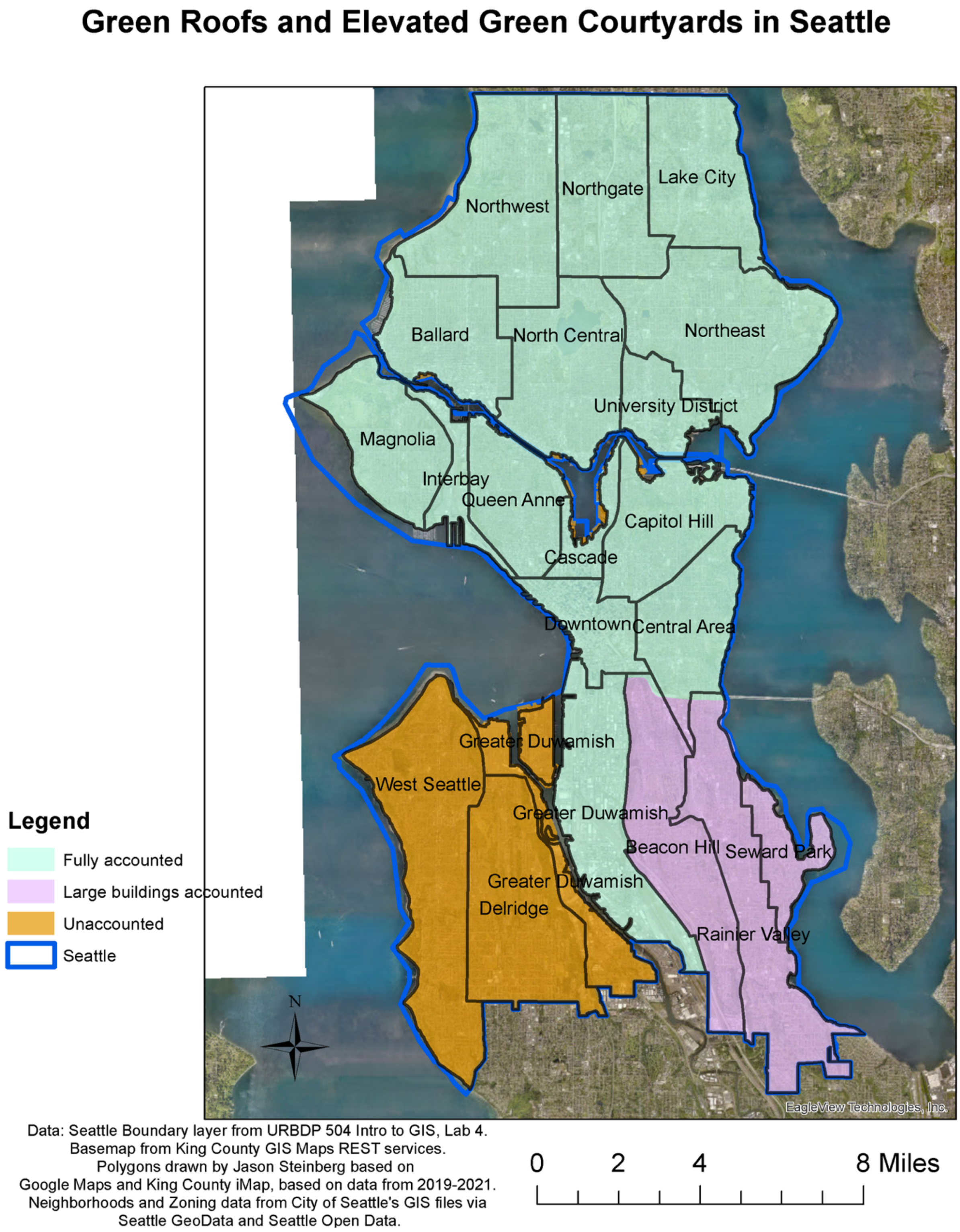
Accounted, Partially Accounted, and Unaccounted Areas in Seattle over Aerial Imagery


Green Roofs and Elevated Green Courtyards in Seattle

Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4.
Basemap from King County GIS Maps REST services.
Polygons drawn by Jason Steinberg based on
Google Maps and King County iMap, based on data from 2019-2021.
Neighborhoods and Zoning data from City of Seattle's GIS files via
Seattle GeoData and Seattle Open Data.

Figure 25

Neighborhoods Overlaying Accounted, Partially Accounted, and Unaccounted Areas



Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4.
Basemap from King County GIS Maps REST services.
Polygons drawn by Jason Steinberg based on
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Neighborhoods and Zoning data from City of Seattle's GIS files via
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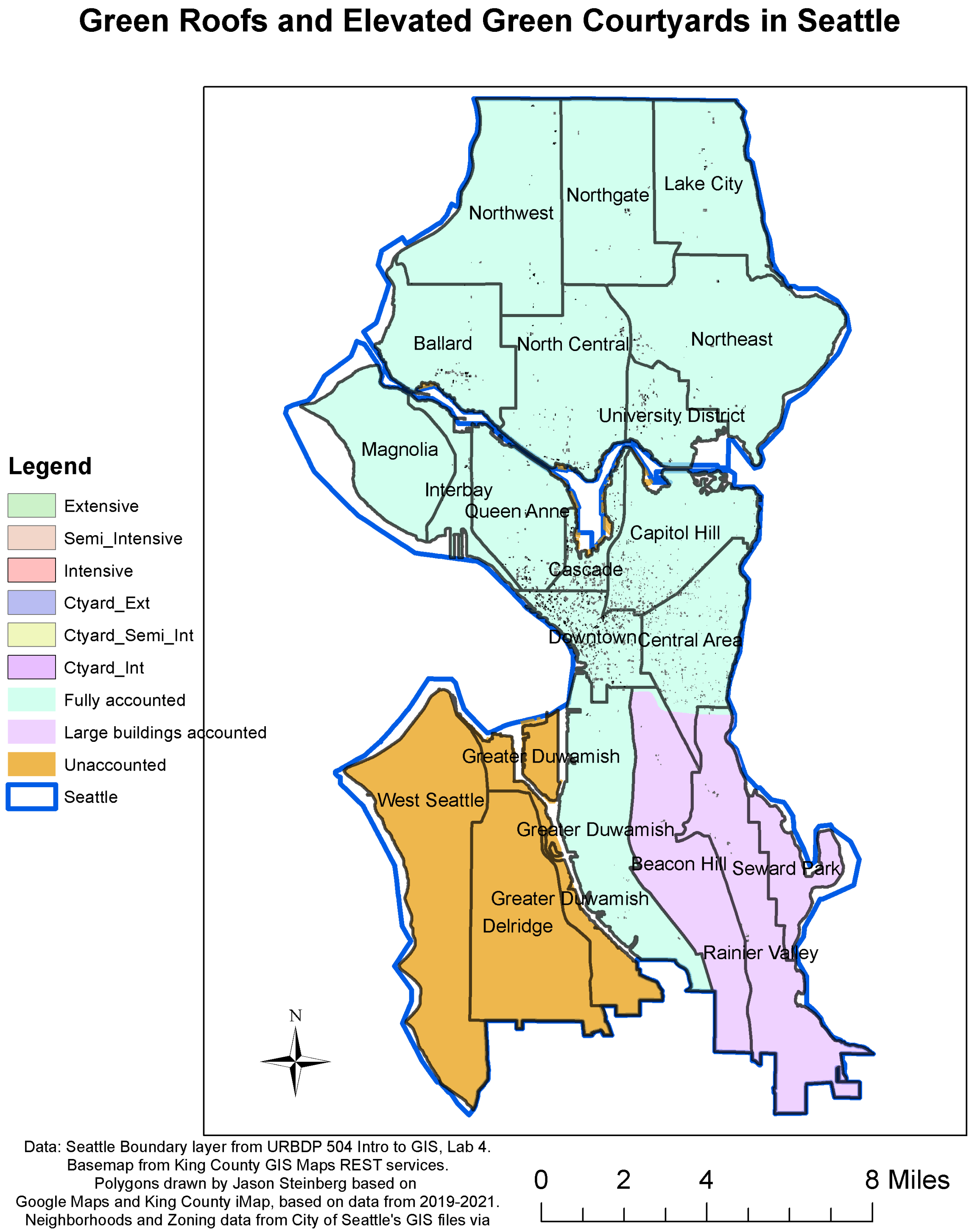
Figure 26

Green Roofs and Elevated Green Courtyards over (Un)Accounted Areas and Neighborhoods



Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4.
Basemap from King County GIS Maps REST services.
Polygons drawn by Jason Steinberg based on
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Neighborhoods and Zoning data from City of Seattle's GIS files via
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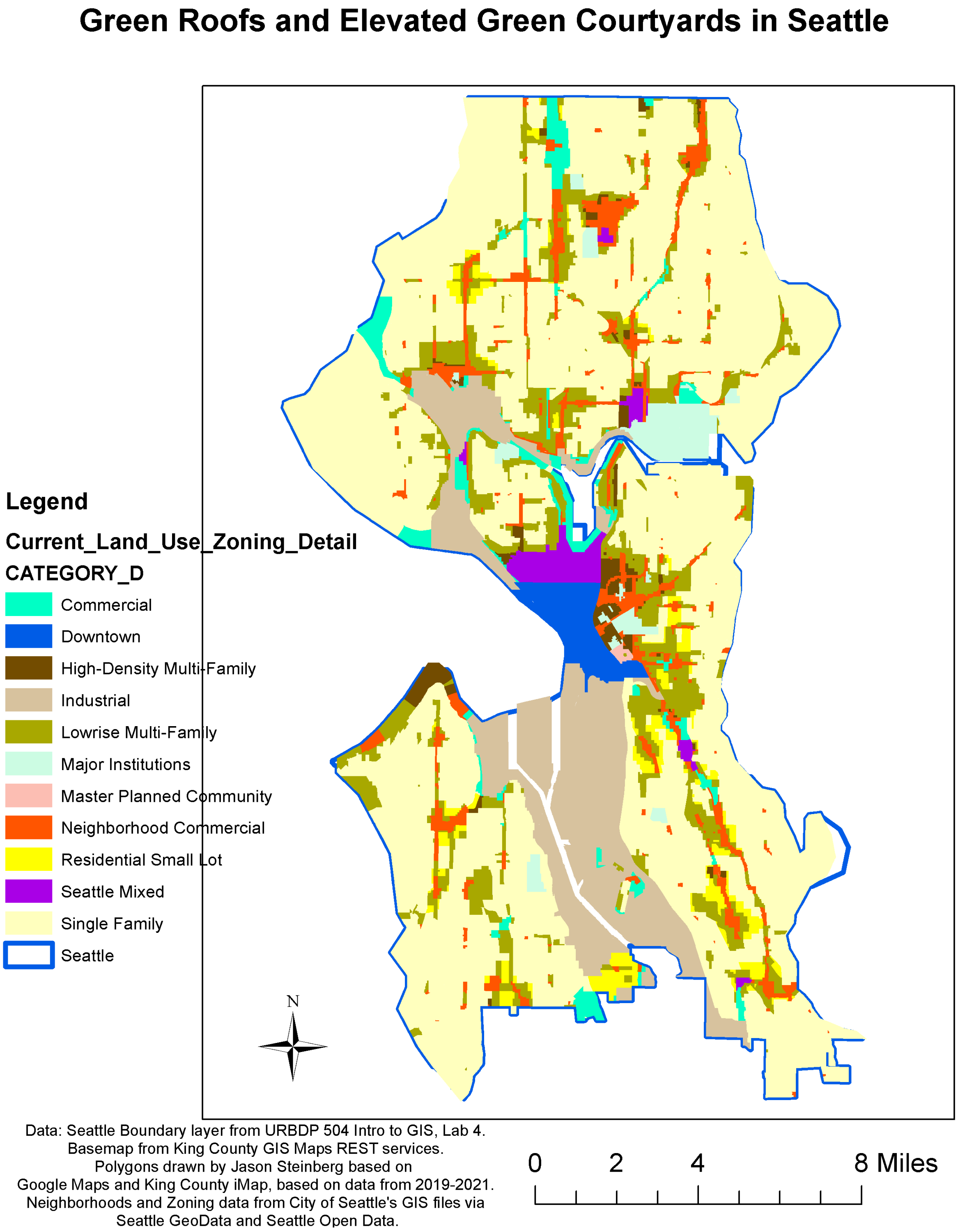
Figures 27 and 28 show the land uses in Seattle, generally and by neighborhood. These are divided approximately into the land uses where vegetation is observed and drawn out and the land uses where they are partially or not at all drawn out, shown in Figures 29 and 30. The density of green roofs and elevated green courtyards in the land uses in the accounted areas are analyzed and calculated to approximate the amount of green roofs and courtyards in the land uses not accounted. Table 5 shows the calculations of these densities.

Figure 27

Land Use in Seattle



Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4.
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Neighborhoods and Zoning data from City of Seattle's GIS files via
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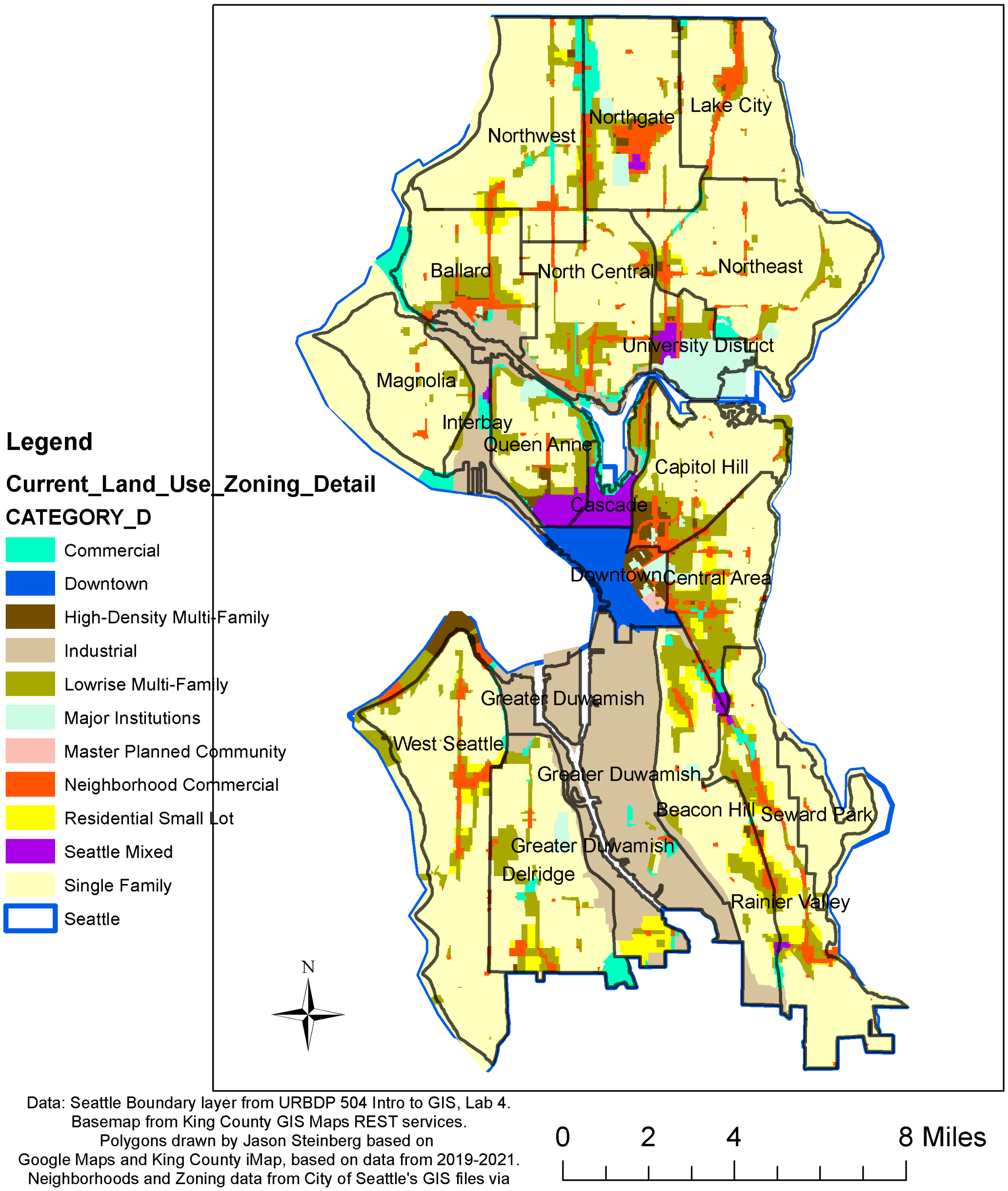
Figure 28

Land Use in each Seattle Neighborhood



Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4.
Basemap from King County GIS Maps REST services.
Polygons drawn by Jason Steinberg based on
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Neighborhoods and Zoning data from City of Seattle's GIS files via
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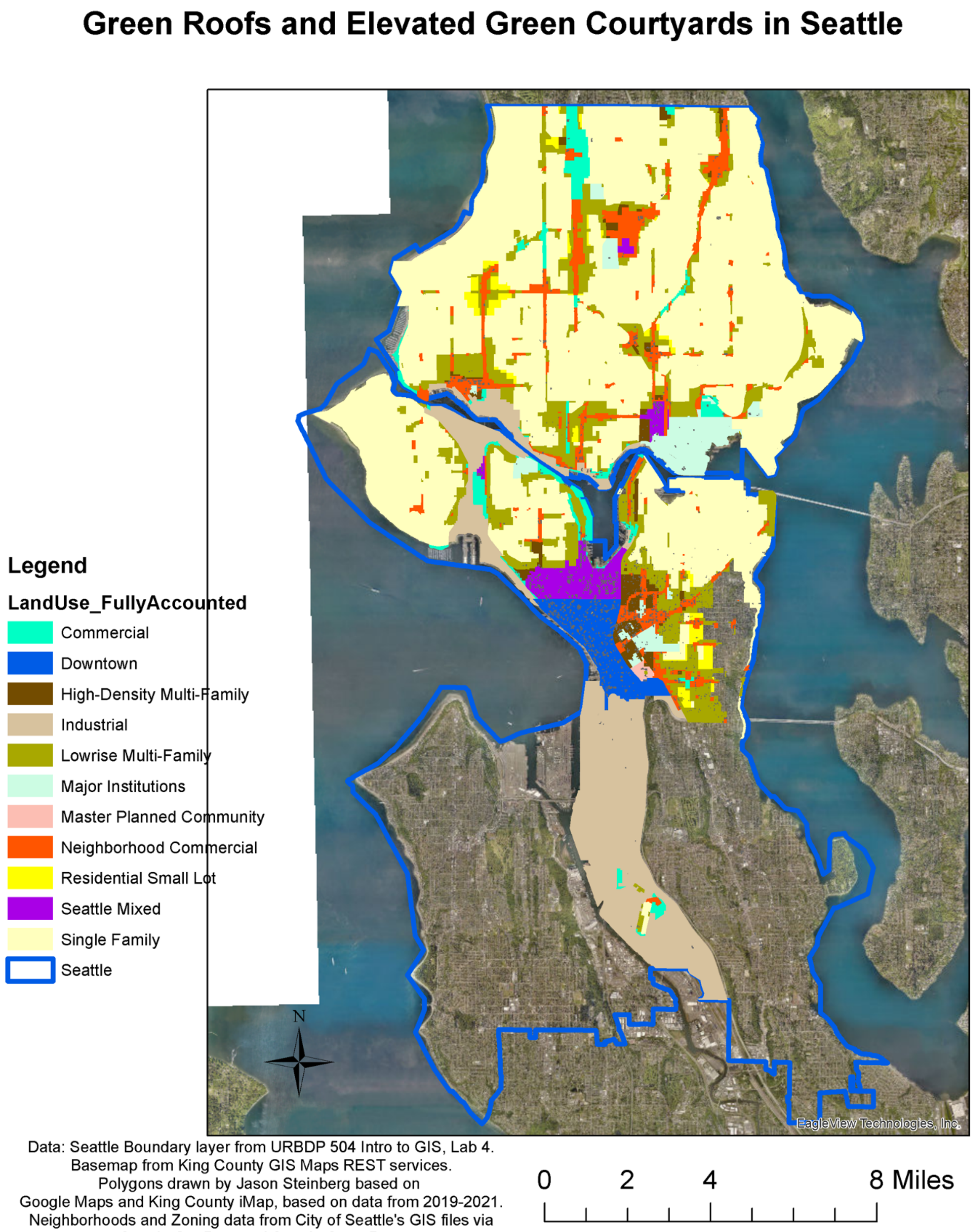
Figure 29

Land Use of Areas for which Green Roofs and Elevated Green Courtyards are Accounted



Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4.
Basemap from King County GIS Maps REST services.
Polygons drawn by Jason Steinberg based on
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Neighborhoods and Zoning data from City of Seattle's GIS files via
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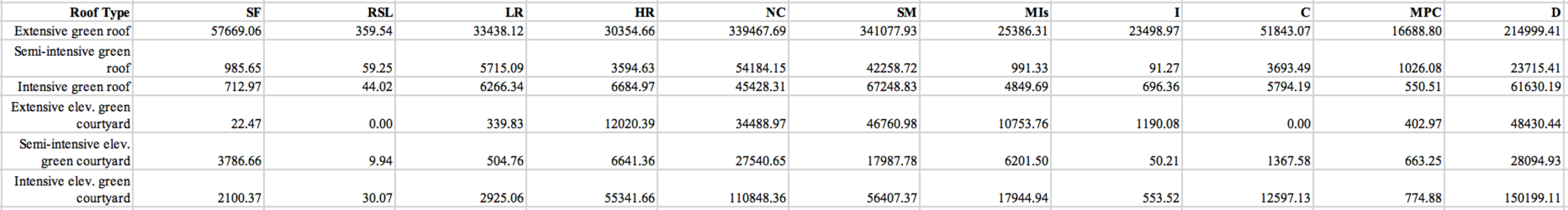
Table 5

Square Feet of Each Category of Green Roof and Elevated Green Courtyard within Each Land Use in Accounted Areas



Roof Type	SF	RSL	LR	HR	NC	SM	MIs	I	C	MPC	D
Extensive green roof	57669.06	359.54	33438.12	30354.66	339467.69	341077.93	25386.31	23498.97	51843.07	16688.80	214999.41
Semi-intensive green roof	985.65	59.25	5715.09	3594.63	54184.15	42258.72	991.33	91.27	3693.49	1026.08	23715.41
Intensive green roof	712.97	44.02	6266.34	6684.97	45428.31	67248.83	4849.69	696.36	5794.19	550.51	61630.19
Extensive elev. green courtyard	22.47	0.00	339.83	12020.39	34488.97	46760.98	10753.76	1190.08	0.00	402.97	48430.44
Semi-intensive elev. green courtyard	3786.66	9.94	504.76	6641.36	27540.65	17987.78	6201.50	50.21	1367.58	663.25	28094.93
Intensive elev. green courtyard	2100.37	30.07	2925.06	55341.66	110848.36	56407.37	17944.94	553.52	12597.13	774.88	150199.11

Note. SF = Single-family. RSL = Residential small lot. LR = Lowrise. HR = Highrise. NC= Neighborhood Commercial. SM = Seattle Mixed. MIs = Major Institutions. I = Industrial. C = Commercial. MPC = Master Planned Communities. D = Downtown.

Table 6

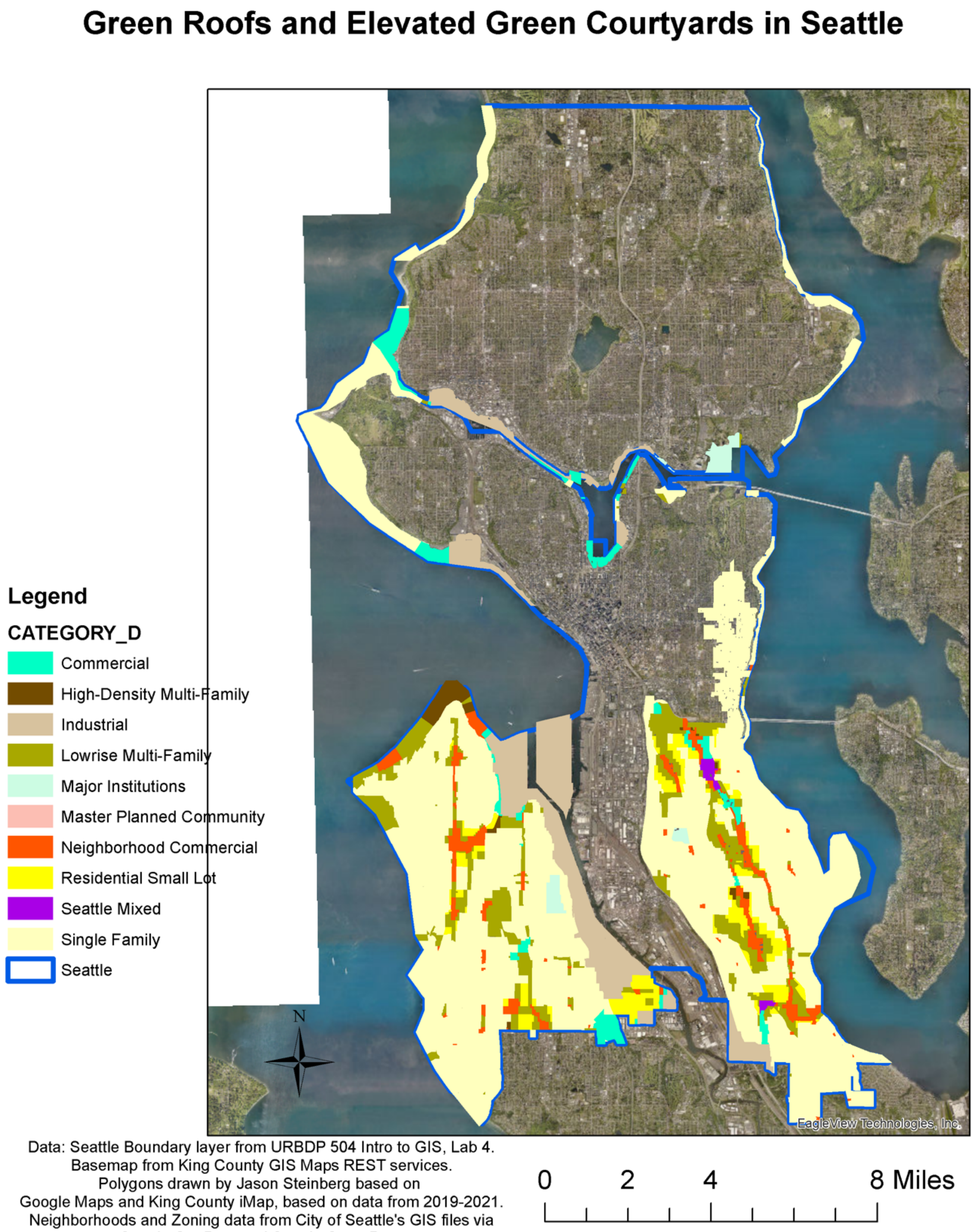
Percentage of Each Category of Green Roof and Elevated Green Courtyard within Each Land Use in Accounted Areas

Roof Type	SF	RSL	LR	HR	NC	SM	MIs	I	C
Extensive green roof	0.006632	0.002026	0.019825	0.133280	0.389759	1.103111	0.058818	0.012360	0.145102
Semi-intensive green roof	0.000113	0.000334	0.003388	0.015783	0.062211	0.136673	0.002297	0.000048	0.010338
Intensive green roof	0.000082	0.000248	0.003715	0.029352	0.052158	0.217496	0.011236	0.000366	0.016217
Extensive elev. green courtyard	0.000003	0.000000	0.000201	0.052779	0.039598	0.151234	0.024916	0.000626	0.000000
Semi-intensive elev. green courtyard	0.000435	0.000056	0.000299	0.029161	0.031621	0.058176	0.014368	0.000026	0.003828
Intensive elev. green courtyard	0.000242	0.000169	0.001734	0.242992	0.127270	0.182432	0.041577	0.000291	0.035258

Note. While this shows percentages, proportions (1/100th of these numbers) are used in calculations for estimating square footage in unaccounted areas. SF = Single-family. RSL = Residential small lot. LR = Lowrise. HR = Highrise. NC= Neighborhood Commercial. SM = Seattle Mixed. MIs = Major Institutions. I = Industrial. C = Commercial.

Figure 30

Land Use of Areas for which Green Roofs and Elevated Green Courtyards are Unaccounted



Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4.
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Table 7

Estimated Square Feet of Each Category of Green Roof and Elevated Green Courtyard within Each Land Use in Unaccounted Areas

Roof Type	SF	RSL	LR	HR	NC	SM	MIs	I	C
Extensive green roof	37491.06	841.65	16887.68	4008.12	137975.14	36344.93	3430.97	12010.14	29007.37
Semi-intensive green roof	640.78	138.70	2886.36	474.65	22022.91	4503.05	133.98	46.65	2066.59
Intensive green roof	463.50	103.06	3164.77	882.70	18464.14	7165.97	655.44	355.90	3241.98
Extensive elev. green courtyard	14.61	0.00	171.63	1587.21	14017.89	4982.80	1453.38	608.24	0.00
Semi-intensive elev. green courtyard	2461.73	23.27	254.92	876.94	11193.77	1916.76	838.14	25.66	765.19
Intensive elev. green courtyard	1365.46	70.38	1477.28	7307.47	45053.82	6010.71	2425.27	282.90	7048.38

Note. Unaccounted additionally refers to partially accounted areas in this context.

Table 8

Square Feet of Each Category of Green Roof and Elevated Green Courtyard within Each Neighborhood in Accounted Areas

Roof Type	**NW**	**NG**	**LC**	**B**	**NC**	**UD**	**NE**	**M**	**IB**	**QA**	**C**	**CH**	**D**	**CA***	**EGD**
Extensive green roof	17,272.21	30,494.93	33,114.18	85,163.42	115,964.05	71,978.66	57,689.38	-	8,033.05	137,715.44	181,941.22	92,738.48	252,433.93	48,361.18	19,417.46
Semi-intensive green roof	3,244.54	295.06	1,070.76	7,129.67	11,814.68	8,227.62	8,142.38	119.08	142.17	25,734.26	17,417.40	18,240.30	28,880.45	6,255.42	290.14
Intensive green roof	2,188.01	-	2,346.01	10,425.36	9,211.33	13,106.90	6,893.12	-	1,519.10	17,992.00	47,222.47	16,641.42	68,526.39	5,040.46	481.87
Extensive elev. green courtyard	612.87	3,114.41	-	1,607.22	2,349.22	9,039.48	6,756.12	-	1,147.46	14,260.12	34,907.97	15,342.86	59,747.69	4,711.49	833.69
Semi-intensive elev. green courtyard	1,840.03	4,190.56	772.94	2,731.11	1,277.85	4,186.42	1,808.99	31.47	1,358.02	709.97	17,235.03	7,826.07	40,512.03	8,536.32	52.98
Intensive elev. green courtyard	15,677.81	8,360.52	3,439.84	23,390.51	15,930.47	15,753.31	6,492.71	389.37	818.31	35,120.87	30,940.54	27,571.70	209,399.42	16,045.82	257.66

Note. *CA (Central Area) has a portion at the far southern end which has not been fully accounted. NW = Northwest. NG = Northgate. LC = Lake City. B = Ballard. NC = North Central. UD = University District. NE = Northeast. M = Magnolia. IB = Interbay. QA = Queen Anne. C = Cascade. CH = Capitol Hill. D = Downtown. CA = Central Area. EGD = Eastern Greater Duwamish.

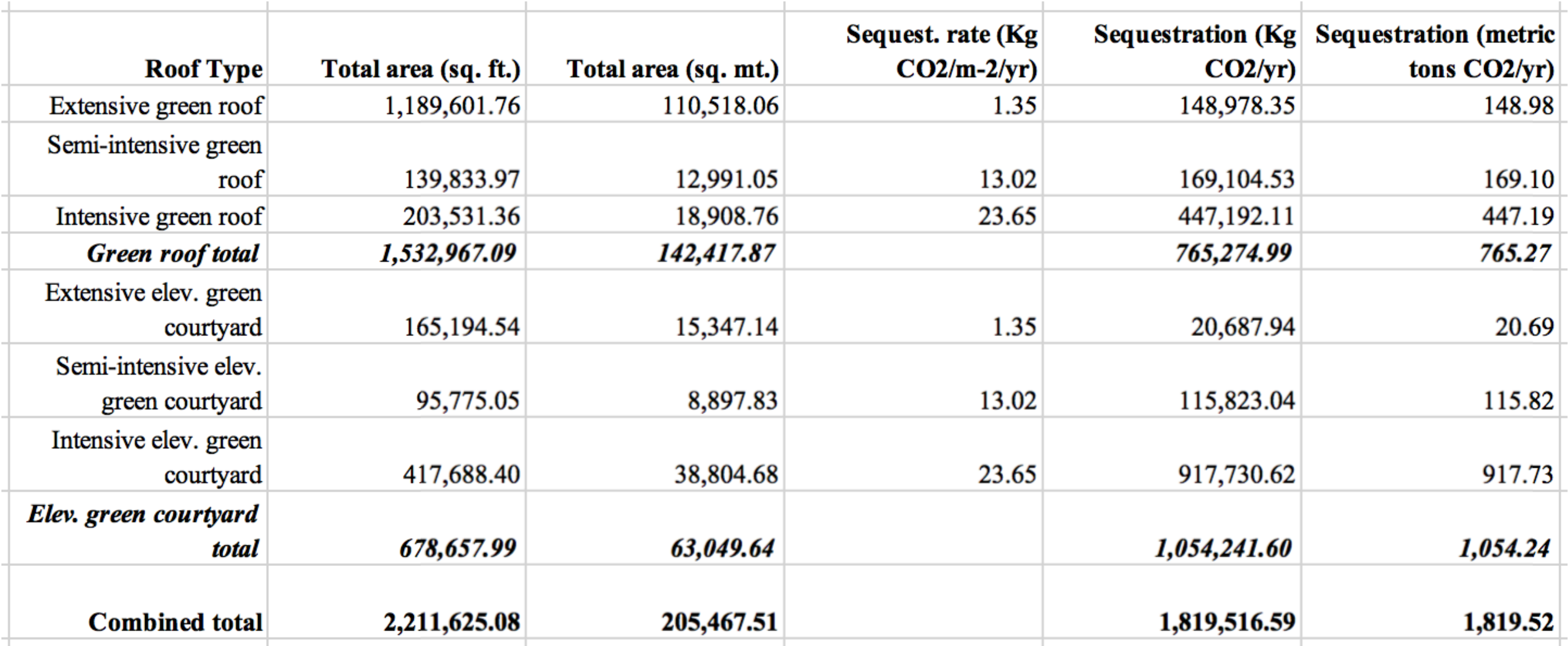
Table 9

Estimated Square Feet of Each Category of Green Roof and Elevated Green Courtyard within Each Neighborhood in Unaccounted Areas

Roof Type	West Seattle	Delridge	Western Greater Duwamish	Beacon Hill	Rainier Valley	Seward Park
Extensive green roof	56,144.76	46,487.74	11,942.94	57,739.07	68,505.04	3,159.24
Semi-intensive green roof	7,408.87	4,738.15	466.18	7,303.10	9,551.57	270.02
Intensive green roof	6,705.66	5,112.80	683.84	8,172.81	9,462.71	226.53
Extensive elev. green courtyard	4,962.48	3,095.22	615.05	5,640.58	6,159.03	146.99
Semi-intensive elev. green courtyard	4,418.14	3,106.33	202.28	3,893.17	4,721.39	225.72
Intensive elev. green courtyard	18,159.58	11,479.92	1,086.91	14,164.15	18,949.98	534.65

Table 10

Summary Data on Accounted Green Roof and Elevated Green Courtyard Area and Sequestration



Roof Type	Total area (sq. ft.)	Total area (sq. mt.)	Sequest. rate (Kg CO2/m-2/yr)	Sequestration (Kg CO2/yr)	Sequestration (metric tons CO2/yr)
Extensive green roof	1,189,601.76	110,518.06	1.35	148,978.35	148.98
Semi-intensive green roof	139,833.97	12,991.05	13.02	169,104.53	169.10
Intensive green roof	203,531.36	18,908.76	23.65	447,192.11	447.19
Green roof total	***1,532,967.09***	***142,417.87***		***765,274.99***	***765.27***
Extensive elev. green courtyard	165,194.54	15,347.14	1.35	20,687.94	20.69
Semi-intensive elev. green courtyard	95,775.05	8,897.83	13.02	115,823.04	115.82
Intensive elev. green courtyard	417,688.40	38,804.68	23.65	917,730.62	917.73
Elev. green courtyard total	***678,657.99***	***63,049.64***		***1,054,241.60***	***1,054.24***
Combined total	**2,211,625.08**	**205,467.51**		**1,819,516.59**	**1,819.52**

Table 11

Summary Data on Unaccounted Green Roof and Elevated Green Courtyard Area and Sequestration

Roof Type	Total area (sq. ft.)	Total area (sq. mt.)	Sequest. rate (Kg CO2/m-2/yr)	Sequestration (Kg CO2/yr)	Sequestration (metric tons CO2/yr)
Extensive green roof	277,997.05	25,826.77	1.35	34,814.49	34.81
Semi-intensive green roof	32,913.66	3,057.78	13.02	39,803.11	39.80
Intensive green roof	34,497.46	3,204.92	23.65	75,796.33	75.80
Green roof total	***345,408.17***	***32,089.47***		***150,413.93***	***150.41***
Extensive elev. green courtyard	22,835.76	2,121.51	1.35	2,859.80	2.86
Semi-intensive elev. green courtyard	18,356.40	1,705.37	13.02	22,198.74	22.20
Intensive elev. green courtyard	71,041.68	6,599.99	23.65	156,089.71	156.09
Elev. green courtyard total	***112,233.83***	***10,426.86***		***181,148.25***	***181.15***
Combined total	**457,642.00**	**42,516.33**	**-**	**331,562.18**	**331.56**

Note. Unaccounted additionally refers to partially accounted areas in this context. Data used for this summary comes from green roof/elevated green courtyards estimates based on land uses.

Combining the results from Tables 10 and 11 of both accounted and unaccounted green roofs and elevated green courtyards gives 2,669,267 sq. ft., or 247,984 sq. mt., or a little less than 0.1 sq. miles. In total, green roofs and elevated green courtyards sequester approximately 2,151,079 kg of CO_2 per year, or 2,151 metric tons of CO_2 per year.

Particular map data conditions require adjustments or qualifications. For example, the city land use map includes several areas which are within city boundaries but are completely or almost completely water. These areas, in the process of mapping accounted and unaccounted areas, show up as unaccounted areas. However, to increase accuracy when estimating amount of green roofs and elevated green courtyards in unaccounted areas based on accounted areas, the portions of mostly-water are manually removed since there clearly are not green roofs or elevated green courtyards in this area. It must be noted that the land use map has many small shapes and the overlap of these small shapes with accounted and unaccounted areas does not line up 100% accurately, but it is for the most part highly accurate. Another land use issue is based on the shapes of the land use shapefiles. A particular area of the Central District is manually observed and recorded; however, this area of single-family land use stretches down to another part of the city which is not manually observed and recorded. When making selections on ArcMap which involve multiple layers, a consistent and mostly-accurate way of selecting shapes in particular categories is when the centroid of a shape is within the other shape, usually indicating most of an area of interest is included. This method usually is highly accurate. However, this method can lead to an issue like a significant portion of the Central Area being excluded because a very large land use area means that the centroid is not within that area. For this portion of the Central Area, it is simply included in the unaccounted area for the sake of land use analysis, even though the green roofs and elevated green courtyards in those areas are included elsewhere as data where applicable. While that portion of the Central Area's land use is shown as unaccounted even though it is, a slightly different issue also occurs where there is a portion of the Central Area (the diagonal portion at the southern end) which is in the 'partially accounted' category, and has land use visualized there which accurately shows that it is not fully accounted, but the neighborhood analysis has the Central Area in the 'fully accounted' category. This analysis shows how many of each type of green roof and elevated green courtyard is in each neighborhood, and the Central Area is included because the overwhelming majority is fully documented in terms of green roofs and elevated green courtyards. This means that there is a slight undercounting of the amount of green roofs and elevated green courtyards when examining the Central Area as an individual unit. One other adjustment is dividing up one neighborhood (the "Greater Duwamish") into multiple parts to accurately categorize areas completely observed and those areas that are not; the portion of the neighborhood east of the Duwamish River is fully accounted.

4.2: Qualitative Insights

While significant forethought and early piloting helped prepare for the mapping process, the extraordinary diversity and complexity of Seattle's buildings, vegetation, topography, and interactions among these led to many considerations and adjustments throughout the mapping process. A number of the topics below discuss in more detail strategies formulated in Chapter 3 (the Methods). A couple of examples are also shown to help visualize the mapping process and some of its challenges.

The framework has been created such that elevated courtyards could generally not be accessible from the street level to be considered an elevated courtyard. However, sometimes a courtyard is 1 or 2 stories above ground level on one side of the building, and at ground level on the other side of the building. In these cases, it was generally decided to include the vegetation in the courtyard on the side which is 1 or 2 stories above ground level, but not the vegetation that is at ground level on the other side. It could also be the case that an elevated courtyard is accessible at the ground level, but more elevated than a courtyard which is not accessible from the ground level. Another possibility could be two courtyards that are the same height, and one is accessible from ground-level while another is not. This example is shown in Figure 15 in Chapter 3.

If elevated courtyards for a building are not ground-accessible at all, they were included. If the courtyards stretched across the entire building from end to the other, generally any end which was not ground-accessible was considered for a subjectively significant portion of the vegetation- typically further than just the highest-up vegetation from ground-level, but less far than reaching the actual ground-level- approximately half of the vegetation in between would be included. If the courtyards did not stretch across entire buildings and were accessible from one end, or there were ground-level accessible areas in between two ends of the building which were not directly ground-accessible, they were usually not included. There were exceptional circumstances, however, which do not necessarily follow the aforementioned rules based on subjective judgments, including on functionality. For example, in northern Seattle, there was a ground-accessible elevated courtyard, yet it appeared to be one of the largest functions of the building, and appeared as a mostly-isolated, stand-alone feature in the development.

Regarding determination of green roof vs. elevated courtyard, as is mentioned in Chapter 3, the absolute top level, the level below that, and potentially the level below that is generally considered green roofs while everything below that is generally considered elevated courtyards. There are some cases however, where several levels below the top, a vegetative level is considered a green roof; this is generally when the functionality is purely for the vegetation and without pedestrian access, while also generally part or all of a major and distinct portion of a building. On the other hand, though green roofs were generally on the top few levels of a building, it could be the case where the vegetation one or two floors below the top level would classify as being on an elevated courtyard in a very low-rise building (e.g., 3 or less floors). Again, the specifics of the building and site help in determining the category in which a set of vegetation should be placed. An overly rigid classification system is avoided due to the concern that strictly stratifying categories would lead to inaccurate categorizations of vegetative levels (courtyard vs. roof) from the point of view of relatively popular conceptions of what a vegetated roof area or elevated courtyard would be, such that this data is more intuitively understandable to anyone who examines this data in the future. The emphasis overall is to have specific enough definitions for the sake of clear categorization while still being flexible enough to be intuitive. For example, this author thinks that most people would likely agree that an externally vegetated second-to-top floor on a 50-story building would still be intuitively considered a roof or "rooftop" area; on the other hand, an externally vegetated second-to-top floor on a 3-story building may well be perceived more as a courtyard than a roof or "rooftop" area. This still may depend on the function- an extensive green roof with no pedestrian access may be considered a rooftop even if it is on the second of three floors or the 49th out of 50 floors; alternatively, an intensively vegetated amenity space with pedestrian access could be considered a 'courtyard' whether it is on the second of three floors or the 49th of 50 floors. In this analysis, though, it is considered clearer to generally have the 49th of 50 floors be considered a roof whether it is extensive without pedestrian access or intensive with pedestrian access (or any other category); in the same fashion, it generally makes more sense to have the second of three floors be considered a courtyard. Still, specific building design factors can affect this judgment. Hypothetically, if a building is three floors, but the third floor is a narrow corridor while the second floor exists across the whole building footprint, and the roof on the second floor is vegetated (with or without pedestrian access), it is likely considered a roof. It is not feasible to describe every potential building design, topographical situation, and building design-topography interactions- the explanation above serves as a general guide to the thinking behind roof versus elevated courtyard classifications in this analysis. Arguably more important than the precise classification is the type/intensity of the vegetation, regardless of building location, since that is most directly relevant to this thesis on carbon sequestration. Related to that point, one assumption is that equal sequestration rates are used for green roofs and courtyards; however, elevated green courtyards seem to have, on average, larger trees. A more specific approach could be useful.

There is varying success with the methods of vegetation classification- it can be challenging to clearly determine height of vegetation on 2-D imagery, and 3-D can have its challenges as well because of distorted renderings. Street view and other photographs have varying success based on photograph locations in relation to vegetation location. In many instances, especially for elevated green courtyards, shadows from buildings can make it challenging to determine if figures are actually vegetative elements, furniture, or even specks of light or pixelated illusions appearing as foliage. Another challenge is that vegetation is not always the same between the 2-D image, the 3-D rendering, and photographs due to the images being taken at different times from each other. This is when it becomes useful to examine aerial images and street views in different years. When there is vegetation that is challenging to classify, using a variety of these methods and a number of years can lead to clarity. Other times, it is challenging to have a clear view of the vegetation no matter the perspective, and so an educated guess is usually made based on the visuals that are seen. One example of this is when high-rises have elevated green courtyards, and some of the courtyard vegetation is behind the building in the 2-D basemap upon which the drawing/measuring of the vegetation takes place. Using the 3-D visualizer in Google Earth is helpful for this, as it allows for spinning around the buildings and often shows how large of an area the vegetation takes up; using clues like 'landmarks' on buildings where vegetation start or end, or using the size and location of other plantings on the courtyard to provide context and match sizes if landscape patterns seemed evident, are methods of estimating the proper size of the drawing on the 2-D image. In these situations, the drawing ends up going 'onto' the building, but represents the vegetation behind it.

In terms of years of the basemap and Google Maps, it is first the case that the basemap was more recent than the Google Maps visualization. In this case, if the building was finished in the basemap and showing green roofs then it was included, even if it wasn't finished in Google Maps. The exception to this, however, was when the height of the level of vegetation on the finished building was indecipherable, thus making it unclear to which category the vegetation belonged since it could not be checked in the 3-D map; in this situation, the vegetation was not included. Later in the mapping process the 3-D map became more recent than the basemap; during this time, if a building was unfinished in the basemap but finished in the 3-D map, then it was not included (Google, 2021; King County/Aerials Express, n.d.).

A set of visual examples can demonstrate insight into the mapping process. Figure 31 shows a few perspectives of a building in Seattle.

Figure 31

Perspectives of a building in Seattle

Note. Clockwise from top-left: A 3-D Google Maps view of the building. A 2-D King County iMap view of the building. The building vegetation mapped (green = ext. roof, tan = semi-int. roof, red = int. roof, yellow = semi-int. courtyard, purple = int. courtyard). Photo of its roof by author. Top left image from Google Maps (2021), Copyright by Google. Right two images from King County (2017/n.d.). Public permission.

The example in Figure 31 is relatively straightforward, though it is clear that careful and varied observation (some not shown here) are useful for accurately labeling vegetation.

At first, the elevated courtyard may not be visible due to shadows. Close examination, in addition to panning the 3-D Google Maps camera help show the building dimensions in ways that are challenging or impossible with purely 2-D views. This includes confirming that there are not ground-accessible paths to the elevated courtyard.

Regarding vegetation intensity, one can tell that each particular perspective provides unique insights. An important note is that timing can play a role in vegetation intensity categorization. Different images can show plants at different ages, different times of year, different amounts of time without maintenance, etc. Distortions can also affect judgments in the 3-D view. Street View on Google Maps can sometimes provide additional insight.

One can notice in the photograph by the author that one piece of vegetation further away is approximately the same height as the taller vegetation closer in view. This is not shown in the 3-D Google Maps view, and it is not particularly easily visible in the 2-D King County iMap view.

It is also worth discussing the ambiguity in vegetation intensity. The taller pieces of vegetation are labeled as intensive, though something just slightly smaller could arguably be considered semi-intensive. Vegetation thickness can sometimes play a role in determinations. A fairly tall but extremely thin and non-woody plant could be more likely categorized as semi-intensive. Another example is the extensive portion of the roof. If the grass was a bit taller and just slightly bushier, it could be considered semi-intensive. It already appears taller than typical extensive green roof vegetation, but smaller than typical semi-intensive vegetation. And again, the timing of maintenance can play a role in these observations. These judgments often come down to individual plants and their multi-dimensional sizes.

Lastly, one can see on the mapping picture that some of the extensive is not included. This is done purposefully throughout the mapping process to not include building equipment, bare patches, etc., so as to not overestimate the vegetation.

Regarding a mapping technique situation, it was on building 595 in downtown that the author finally learned how to add a feature to an existing polygon without starting from scratch; an earlier search for a solution to this issue had been unsuccessful and it was decided to continue on. Starting over from scratch was often done when it became clear that vegetative elements were missed in the mapping process, except in a few cases when very time-intensive multi-part polygons had been drawn and/or the unincluded vegetation was relatively negligible on a building scale. Across the entire city, those unincluded portions are minuscule, insignificant, and do not change the general picture of the results. However, it must be realized that for numerous reasons, not every single piece of vegetation was included from every building throughout the city. Almost all have been included, relatively speaking, to the point where this is an unprecedented comprehensive inclusion of building vegetation in Seattle. Future researchers can modify and add to this dataset.

Further, as described above regarding classifications, an attempt was made to be highly consistent, and much thought went into categorizing vegetation. However, when mapping with such a large amount and diversity of vegetation and buildings, it is likely that some inconsistencies in approach may have occurred, such as a type of vegetation that would have been classified as semi-extensive at one point and extensive much later on. Another example is for planter boxes on rooftops- earlier on, an emphasis was usually placed on classifying these as semi-intensive due to the apparent depth of the soil/container, and it was considered that if Google Maps showed a full planter box while the basemap showed an empty planter box that an intermediate approach would be taken and to cover a portion of the planter box. Later in the experiment, the approach was more akin to focusing just on the vegetation in the basemap and classifying the vegetation based on that. Again, the total scale of the results of these different approaches is likely quite small in the vastness of vegetation covered overall.

Chapter 5: Discussion

This thesis uses available aerial and satellite imagery to map out a likely significant majority of Seattle's green roofs and elevated green courtyards, and uses land use data to estimate the unmeasured green roofs and elevated green courtyards. Additionally, green roof carbon sequestration data from numerous studies (see section 3.3) has been used to estimate Seattle's annual green roof and elevated courtyard carbon sequestration. It has been found that the total area of all green roofs and elevated green courtyards is 2,669,267 sq. ft., or slightly less than 0.1 sq. miles. The estimated total CO_2 sequestered in Seattle is 2,151,079 kg CO_2 per year, or 2,151 metric tons. Information is gathered more specifically for types of green roofs and elevated courtyards, as well as data on prevalence in particular land uses and neighborhoods.

5.1: Mapping Results Compared with Previous Research of Seattle

Stenning (2008) analyzed the Seattle Green Factor's implementation shortly after its adoption, and found that there had since been 2.85 acres, or 124,102 sq ft of green roofs implemented, all of which had at least 4" inches of soil. These were atop ~21 buildings. There was no analysis of pre-existing green roofs.

Fairly soon after, McIntosh (2010) took a look at all existing green roofs (emphasizing 1,000+ sq ft green roofs but including any)- she found 62 green roofs equaling 359,375 sq ft. These were broken up into categories- extensive, (186,270 sq ft) intensive (148,069 sq ft), extensive/intensive combination (25,036 sq ft), and agricultural roofs (3,631 sq ft), in addition to some projects beyond the scope of this thesis, such as the Cal Anderson Park lid. McIntosh also categorized green roofs by their building type- also beyond the scope of this specific analysis (McIntosh, 2010).

Eight years later, Matza (2018) attempted to update McIntosh’s (2010) work. Due to logistical challenges, the update was limited, and (uncategorized) 47,643 sq ft were added for a total of 407,018 sq ft.

The same year, Steinberg (2018) performed a similar yet simpler version of this thesis and found 1,443,705.50 sq ft of green roofs and elevated vegetation (uncategorized).

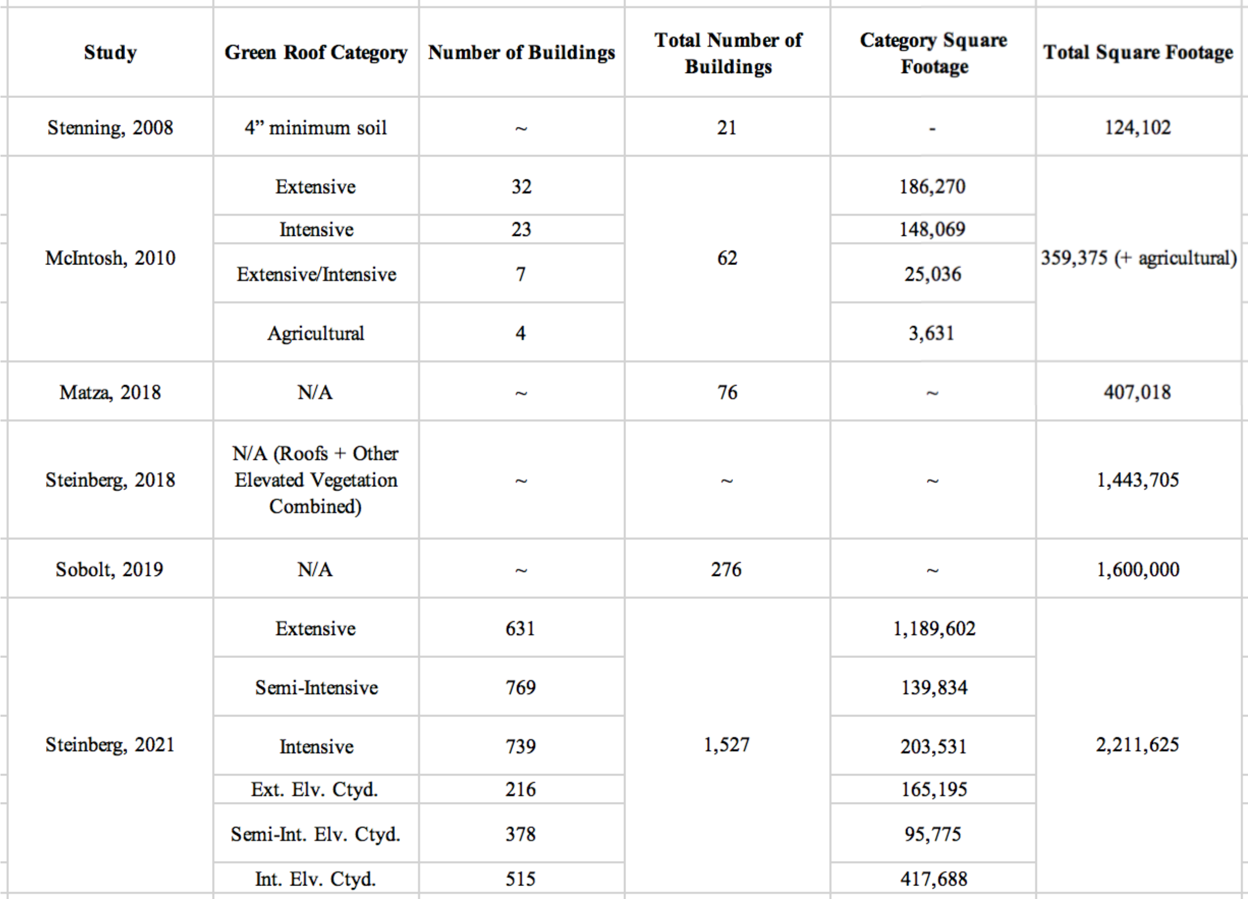
More recently, using data from 2015-2017, Sobolt (n.d./2019) used deep learning and found 345 green roofs, but a manual check lowered this amount to 276 green roofs, taking up ~1,600,000 sq ft (uncategorized), though LaClergue (2020, personal communication) indicated that this was likely an overestimate due to the imprecise automated method, even with the manual check.

Now, this thesis uses imagery primarily from 2019-2020 (and some potentially from 2018 as well as 2021) to examine and manually map green roofs and elevated courtyards as well as estimate others based on land use.

This chain of Seattle green roof research data is summarized in Table 12.

Table 12

Summary of Seattle Green Roof Research to Current Date



Study	Green Roof Category	Number of Buildings	Total Number of Buildings	Category Square Footage	Total Square Footage
Stenning, 2008	4” minimum soil	~	21	-	124,102
McIntosh, 2010	Extensive	32	62	186,270	359,375 (+ agricultural)
	Intensive	23		148,069	
	Extensive/Intensive	7		25,036	
	Agricultural	4		3,631	
Matza, 2018	N/A	~	76	~	407,018
Steinberg, 2018	N/A (Roofs + Other Elevated Vegetation Combined)	~	~	~	1,443,705
Sobolt, 2019	N/A	~	276	~	1,600,000
Steinberg, 2021	Extensive	631	1,527	1,189,602	2,211,625
	Semi-Intensive	769		139,834	
	Intensive	739		203,531	
	Ext. Elv. Ctyd.	216		165,195	
	Semi-Int. Elv. Ctyd.	378		95,775	
	Int. Elv. Ctyd.	515		417,688	

Note. In this thesis, multiple categories of green roofs and elevated green courtyards often exist on one building. Unaccounted green roofs and elevated green courtyards are not included in this table.

While this thesis provides the most detailed mapping of Seattle’s green roofs yet, it is also likely that the author was more liberal about what was considered to be a green roof; even one or two plants on top of a single-family house or townhouse could be included. The rationale is that hundreds or thousands of small or isolated plants, or pockets of plants, can add up. However, it is challenging and time-consuming to do this. Also, while LaClergue (2020, personal communication) noted that Sobolt’s (2019) study included interior courtyards which would not normally count as green roofs, and included entire roofs when only a portion was green, this thesis contained consciously created particular guidelines toward which (elevated) courtyards to include, and efforts were extremely precise when drawing over plants and vegetation so as not to overestimate the amounts thereof. Actually, when there were visual uncertainties, such as plants known to exist yet hidden behind a portion of a building, a slight underestimation, or at least fairly conservative, estimate was undertaken. Alternatively, the resolution limits sometimes meant there were greenish-grayish-brownish shapes that appeared perhaps slightly irregular (indicating vegetation), or if regular then indicative of precise pruning, and these shapes were sometimes included even though it was not entirely certain if they were vegetation. Yet decisions in this regard were consciously made rather than automated like in Sobolt (2019).

This thesis is generally more detailed than the previous works, although some of the other studies included details which this thesis does not. For example, McIntosh did specifically identify agricultural planter boxes on roofs. During the mapping of this thesis, there appeared to be many planter boxes, some of which were almost certainly for agricultural production; however, it can be challenging to always tell when this is or is not actually the case. Additionally, the focus here is subsequently on carbon sequestration, and it is clearer and more backed by research to use the categories of Extensive, Semi-Intensive, and Intensive (Whittinghill et al. (2014) did examine vegetable gardens on a rooftop as well as on the ground; the ground-level garden did sequester carbon and had by far the highest amount of soil carbon content in the experiment, while the vegetable garden on the roof did not have enough data to determine sequestration amount, though it had by far the highest amount of soil carbon among the green roof categories). In addition to the lack of agricultural categorization, this thesis did not measure or have a record of soil depth of the green roofs, while Stenning (2008) did have these records through the SGF worksheet. Knowing the soil depth could increase the accuracy of the carbon sequestration estimates; the categorization of Extensive or Semi-Intensive or Intensive was made based on the perceived size of the vegetation.

5.2: Considerations of Accuracy of the Carbon Sequestration Rates Used for Seattle

No studies of carbon sequestration of green roofs have been performed in Seattle, and the small amount of research that has been done on carbon sequestration in Seattle or urban/community areas in Washington at the ground level were only measuring trees and tree-like shrubs, and the resulting estimates were from equations modeling growth (Ciecko et al., 2012; Nowak et al., 2013). Unlike studies on green roof carbon sequestration, there does not appear to have been direct measurement of carbon in plants over time. This makes sense with naturally-observed trees as it would require cutting them down, but it shows that direct carbon sequestration analyses, including for green roofs (and elevated courtyards) need to be done so that sequestration estimates can be more accurate.

As discussed in section 3.4 and the Appendix, carbon sequestration rates for trees were not used. As already mentioned, there have been no ‘direct’ measurements of carbon changes of trees in Seattle- they have been modeled- and there appear to have been none at all that have measured rooftop tree sequestration in any capacity (Ciecko et al., 2012; Nowak et al., 2013). There were a couple of studies that measured/modeled carbon storage in Seattle trees, but they did not measure carbon sequestration (Hutyra et al., 2011; Tenneson, 2014). Data was available from Tenneson’s (2014) work to estimate some species of trees’ sequestration using the i-Tree Planting tool (described in the Appendix), and the sequestration of those species was quite low overall, especially when considering the square meters they may cover. An overall trend was that carbon sequestration in trees was surprisingly low, often significantly lower than green roofs. It was very surprising that even forests near the Pacific in Oregon had lower sequestration rates than just about all green roofs (Jones et al., 2007). This could all mean that there are measurement issues regarding tree sequestration modeling, issues with the green roof sequestration methods, both, or neither. Perhaps it is partially about how the area of a tree is being measured after getting the sequestration results per tree (discussed in the Appendix). The notion that trees could be sequestering less than green roofs per square meter warrants further investigation. Though Ciecko et al. (2012) and Tenneson (2014) state that small trees can be those considered up to 30 feet tall, and some of the trees seen in the mapping process (especially on the elevated courtyards) could be around that height, it is true that rooftop trees tend to be smaller than this. It is interesting that Hutyra et al. (2011) stated that the small trees in their study were 62% of those measured yet likely less than 5% of total biomass. Though McPherson et al. (2016) stated that some of the biomass/carbon results of older and larger trees may be due to fewer data points, it also seemed to be a common trend for many species of trees to have an increasing rate of growth of biomass/carbon as they get older, while smaller and younger trees tend gain carbon slowly for the first 10-20 years (see Figures 8, 9, and 10).

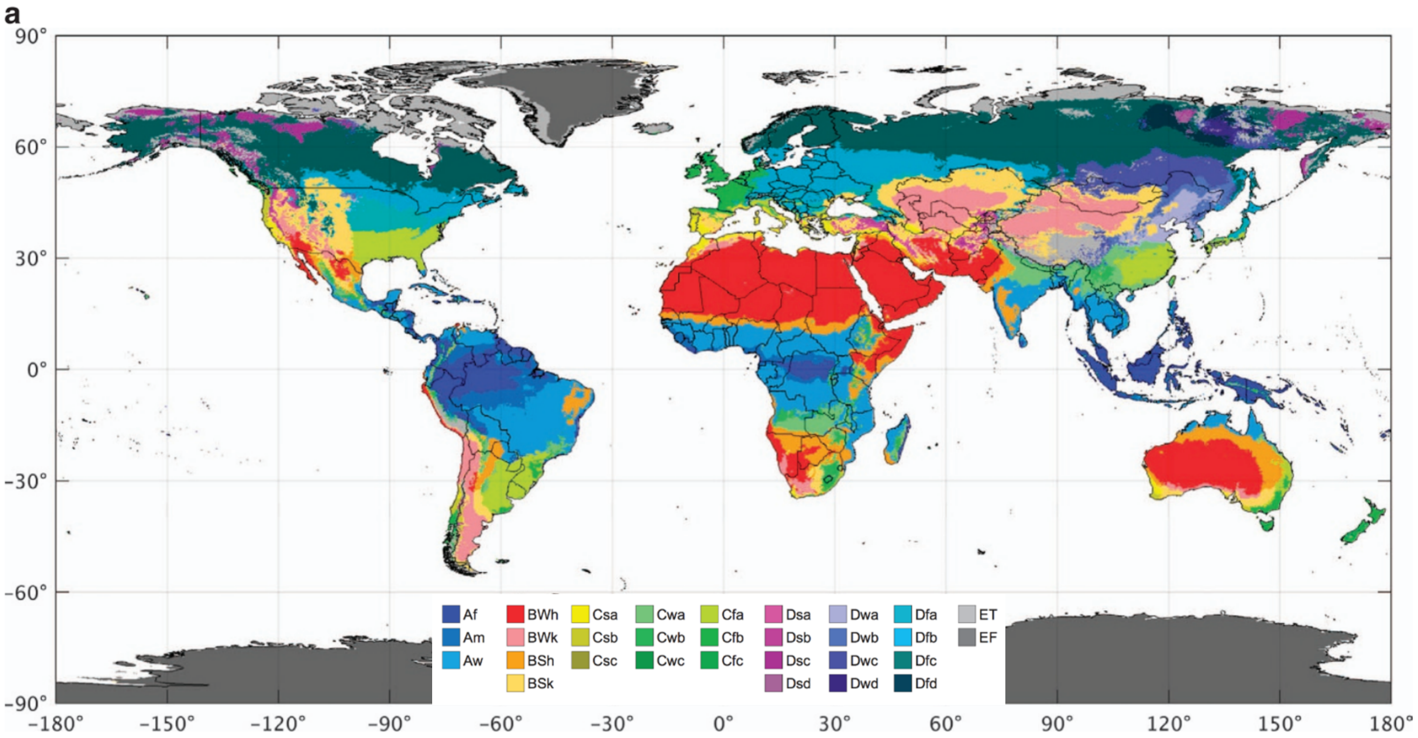
Climate is another consideration. Based on data from McPherson et al. (2016) and Nowak et al. (2013), it seems that urban/community areas in Washington have perhaps an average to above average sequestration rate compared to the rest of the country, likely doing better or worse depending on a variety of conditions. Thinking of plant conditions discussed in Smith & Smith (2015), Seattle has significant precipitation and also lots of sunshine at certain parts of the year, along with a long growing season due to moderated temperatures. There are certainly many plants that have adapted to this Mediterranean-Oceanic-like climate, though the swings in precipitation and sunshine could be a challenge for other plants. Similarly, green roofs (and to a lesser degree elevated courtyards) give plants in urban areas an almost maximum amount of sunlight possible, and precipitation and rain could allow for strong growth. At the same time, the dry summers could be a challenge for plants not easily adapted, or still limit growth of those that are. It would thus make sense to irrigate green roofs in the dry season in order to maximize sequestration. With likely warmer temperatures due to climate change, that could extend the growing season and potentially increase carbon uptake in spring and fall, but that could also make the summer environment more challenging, especially with likely prolonged dry seasons (Climate Impacts Group, 2015).

It could have been effective to go beyond simply determining Köppen-Geiger climate classifications of the cities that studied carbon sequestration of green roofs- measuring annual, seasonal, and monthly temperatures, precipitation, sunshine hours, wind, humidity, and other factors could have led to more insight into what specific types of climates may have sequestered more carbon, and from there perhaps cities with more similar climates could have been weighted more for their use in Seattle calculations. The other experimental conditions and procedures would also have to be taken into consideration to determine what factors were actually increasing the sequestration. Standardized experiments of green roofs in different climates would be beneficial. Relevant to this point as well as the upcoming climatic shifts, Figures 32 and 33 show the current and future climate zones around the world- this can give an indication of where other studies can take place to compare to Seattle, and also shows the forward-thinking that will have to be done when considering vegetation in Seattle and beyond. Even if a climate zone stays the same, there can still be climatic shifts, and changes will also continue beyond the years in Figure

33. To reiterate, though, this is just one climate classification model and gives more of a broad illustration; for strong experiments, the aforementioned annual, seasonal, and monthly patterns should be considered.

Figure 32

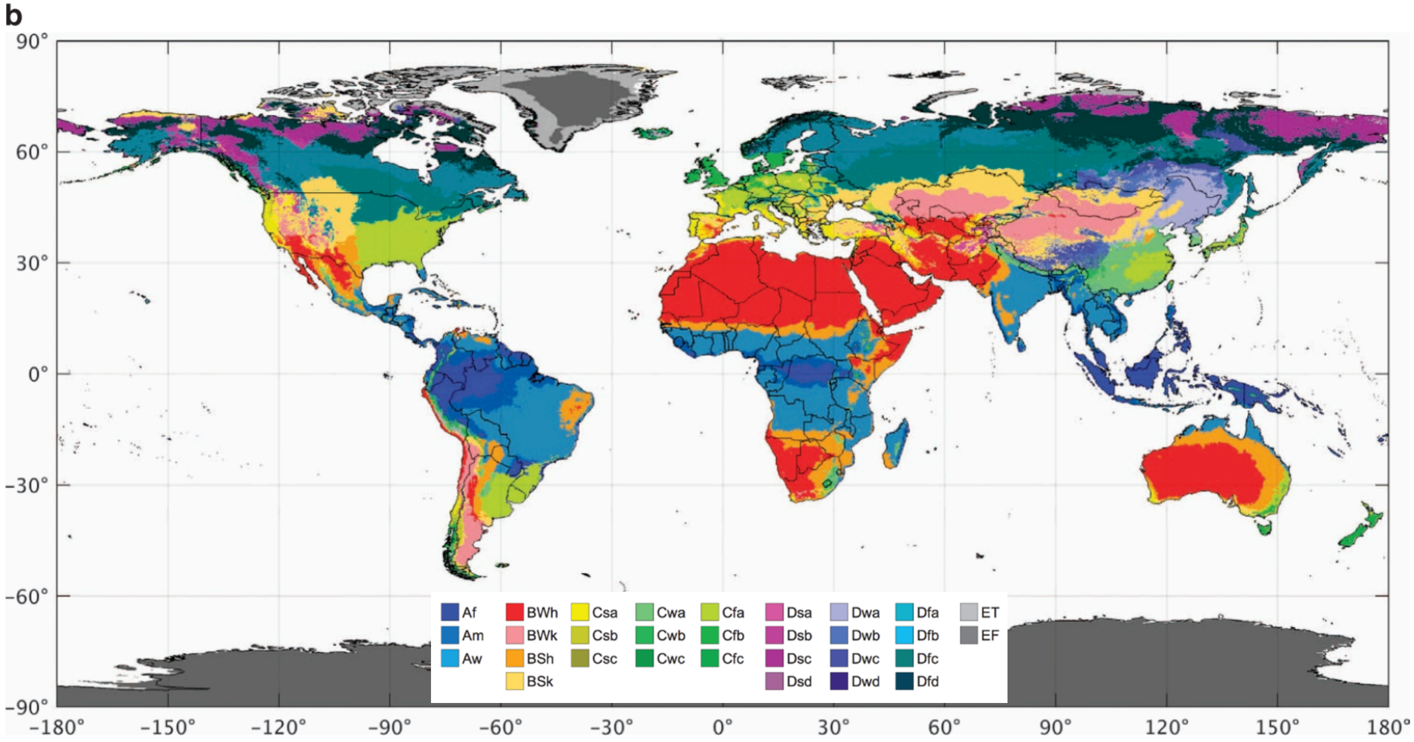
Current Köppen-Geiger Climate Classification Map (Reflecting 1980-2016)



Note. Seattle is currently in the Csb zone (‘temperate, dry summer, warm summer’) with Cfb (‘temperate, without dry season, warm summer’) close to the east. These are the definitions given in Beck et al., 2018. From From “Present and future Köppen-Geiger climate classification maps at 1-km resolution,” by H.E. Beck, N.E. Zimmermann, T.R. McVicar, N. Vergopolan, A. Berg, & E.F. Wood, 2018, *Scientific Data, 5,* p. 3 (https://doi.org/10.1038/sdata.2018.214). CC BY 4.0.

Figure 33

Future Köppen-Geiger Climate Classification Map (Predicting 2071-2100)



Note. Seattle and nearby areas formerly Cfb will change to a Csa zone ('temperate, dry summer, hot summer', hottest month ≥ 71.6 F). These are the definitions given in Beck et al., 2018. From From "Present and future Köppen-Geiger climate classification maps at 1-km resolution," by H.E. Beck, N.E. Zimmermann, T.R. McVicar, N. Vergopolan, A. Berg, & E.F. Wood, 2018, *Scientific Data, 5,* p. 3 (https://doi.org/10.1038/sdata.2018.214). CC BY 4.0.

It is not clear how many of the plants that were studied in the carbon sequestration studies would survive or thrive in Seattle. Experiments with similar climates (in addition to Seattle itself) are scientifically and logistically important for green roof experiments because data can be gathered for a wide variety of plants and roof types while experiencing the similar conditions, while the similar locations can also provide additional data and evidence for similar plants that are being studied in other similar locations. Additionally, climates that are slightly different could provide insights by using the same or similar plants but with different growing conditions (e.g., more or less sun, more or less rain).

Soil could be another important sequestration factor. In this thesis, sequestration rates from other studies that were included in the calculations were those with the most naturalistic soils, as opposed to the more experimental soils. However, some experimental soils like biochar showed promise of greater sequestration than more typical soil (Chen et al., 2018; Luo et al., 2015; Ondoño, Martínez-Sánchez, & Moreno, 2016b).

5.3: Limitations

There were several limitations in this thesis that were either challenging or impossible to overcome for being completely accurate in the processes of mapping and carbon sequestration estimation. Many have been mentioned in earlier sections.

Experiments with different climates, different plants, and likely different soils make using those data an imperfect process- even combining the data from different climates together may not come out to an average that is closer to Seattle, although this would need to be confirmed with more analysis. There is no replacement for experiments under similar or the same conditions. Many of the studies were in other countries, which could mean different materials, access to experimental sites, etc. Additionally, it is not clear how the experimental procedures related to fertilization and irrigation compare to green roof maintenance in Seattle (which itself probably varies even among similar roofs). Regarding the experiments themselves, measurements were sometimes taken at the end of a growing season; if the measurements were taken at different times then the sequestration rates may be different. When standardizing the collection of studies, in normalizing the calculations of sequestration of CO_2 per year in each study that was not 12 months long, there was an assumption of linear change of sequestration rates over time, and this may have led to inaccurate sequestration rates and thus inaccurate calculations in the rest of the experiment.

Procedurally, mapping allowed for examining all of the buildings in Seattle in a much faster way than would have been the case going through official city documents, and city documents would not include all that was measured such as personal or informal plantings. A spreadsheet of addresses which implemented the Seattle Green Factor was received by email—it contained addresses which had relevant documents dating from April 2018 to October 2020—this time frame was related to a permitting system change which made addresses with earlier documents more challenging to find (Lofstedt & Hua, 2020, personal communication). As Matza (2018) found, entering each address into the permitting system, searching for a particular type of document, then looking through that document in order to potentially find the Seattle Green Factor sheet was a timely procedure; it would not have been feasible to find a similar amount of green roof information. It would, however, have provided more details into aspects like soil depth, and if landscaping plans were available, even plant species. A limitation of mapping is that many species are unknown and soil depth is unknown. Maintenance like fertilization and irrigation is unknown as well. These missing factors reiterate the very likely loose estimate of the sequestration rates used in this thesis.

Data that was used—aerial/satellite imagery, street and building-level photography, etc. —were useful, but had pitfalls. One of the largest challenges was vegetation blocked by shadows. Adjacent building shadows would cover large elevated courtyard areas, for example, on all of the satellite/aerial imagery, even after examining aerial imagery from different years. This was of course more common with larger buildings, which exist in a substantial number of Seattle neighborhoods. Similarly, when using street-level views to attempt to determine details about elevated portions of buildings or even rooftops, sometimes every angle and every year of street-level photographs would skip over the necessary section, or would always have a tree blocking the section. It raised the idea of site visits, and while some personal photographs of buildings were used, site visits for every challenging building were not feasible. Additionally, satellite imagery distortions which potentially inaccurately flattened or raised vegetation, differences in vegetation size and landscaping patterns between different data sources, challenges of determining whether or not certain shapes were actually plants due to image resolutions, occasional challenges differentiating artificial turf from extensive green roofs, and other difficulties made data gathering accurately to be time-consuming and impossible to be fully accurate. It seemed higher resolution satellite imagery likely exists but was not financially feasible. Even if clearer images were used, shadows could still prevent accurate data collection. Additionally, shadows are an important challenge or limitation for automated analyses.

5.4: Urban Design Insights and Implications

Though this carbon sequestration estimation project has not allowed for direct experimentation of how particular building and urban design features impact sequestration amounts, numerous insights can be discussed based on literature and observations during the mapping process.

As indicated by Smith & Smith (2015), there are a set of circumstances that generally lead to increased carbon sequestration: substantial sunlight, plentiful water, air flow, warm but moderated temperatures, and nutrients all allow for plants to absorb carbon and grow. A number of these features are relatively plentiful on rooftops and elevated areas compared to other urban environments.

Rooftops are more likely than groundscapes to provide access to the sky and hence sunlight. This benefits shade-intolerant plants in particular (Smith & Smith, 2015). Shade-intolerant plants, when provided adequate sunshine, grow more and absorb more carbon than more shade-tolerant plants. However, shade-intolerant plants can grow on rooftops and allow more shade-tolerant plants to grow underneath. There are circumstances which can affect how much sunlight affects plants, even on rooftops. One example is the presence of other buildings nearby. Relatively tall buildings nearby can block significant amounts of sunshine onto rooftops that are at a lower elevation, and this can drastically affect the carbon sequestration potential and even the plant species suitable for that rooftop. Alternatively, nearby buildings (or landscapes) can have an opposite effect, being light reflectively. If a green roof is surrounded by buildings with white panels and reflective glass that are in the direct path of the sun, or to a lesser extent in the path of sunlight reflecting from water or other buildings, then this can affect the amount of light absorbed by plants. As just alluded to, it is not just surrounding buildings and landscapes that influence light absorption and sequestration. Plants on the rooftop itself can have potentially unexpected influences on other vegetation on the roof. Figure X provides illustrations of how green roof vegetation in Seattle could cast shadows on surroundings.

Figure 34

Shadows Cast by Trees at Different Times of Day in Seattle

Note. Clockwise from top left: trees on a rooftop with the sun coming from the southeast, trees with the sun coming from the south, and trees with the sun coming from the southwest. Created by the author, using Lumion 10.3.2 (Copyright by Act-3D, 2020), SketchUp Pro 2020 (Copyright by Trimble, 2017/2020), and CadMapper (© OpenStreetMap contributors, data available with Open Database License).

When the sun comes from the south and is high in the sky, there are minimal shadows. However, the trees can cast long shadows at other times of day. When the sun is coming from the southwest, one can even notice the shadow of part of a tree on the sidewalk/street below; this can influence the amount of sunlight absorbed by the plants on the street below. Depending on the amount of shadows and other circumstances, these types of factors can have unexpected influences on sequestration. However, more noteworthy than the tree shadow is simply the building shadow onto the street below; this same issue can occur with taller buildings casting shadows onto rooftops. At the same time, shadows can be beneficial. Above certain temperatures, sequestration and plant health decline (Smith & Smith, 2015). Shadows during the hottest parts of the day could actually have beneficial effects on plant health. Additionally, the shape of the roof is important. Many green roofs are flat, but angled green roofs exist, and can be directed at particular angles to optimize sun exposure. Many of these issues apply in similar but perhaps more complex ways for elevated courtyards since they are surrounded by more features in the environment.

Water is vital for plants. Roofs often provide the first access for plants in an urban environment to get water, and can get more since rain does not always fall completely vertically, influencing plants lower to the ground level. It is important to consider seasonal changes and climate change, though. Common throughout the green roof sequestration literature were discussions of irrigation and its likely benefits for plant well-being and sequestration. This is an important consideration in Seattle's dry-summer climate.

Similarly, while wind flow can be quite prominent on rooftops, and wind can facilitate carbon dioxide exchange in plant leaves, too much wind, particularly in hot and dry conditions, can harm plants and reduce sequestration. Building designs which can balance plants' needs of enough sunlight and water along with enough but not too much wind can optimize sequestration. Particular building locations can also create microclimates. Green roofs near the water may have more humidity than green roofs further inland, for example.

Maintenance of plants is an activity which can have both significant influence on plants as well as significant influences on the urban environment. Frequent cutting, sawing, mowing, airblowing, etc. can disrupt people nearby while also likely reducing sequestration and simultaneously emitting carbon dioxide into the atmosphere; there is an open question also of what happens with the plant remains and if they simply decompose (Whittinghill et al., 2014). If green roofs are widespread, there is likely to be more carbon sequestration, but too-frequent maintenance can have disruptive side effects for both plant and human life. Alternatively, as indicated by Haksever (2020) and Zelenski et al. (2015), green roofs and exposure to natural environments can motivate increased vegetative development and cooperative/sustainable behaviors. If green roofs become community gardens, people can take, in a certain sense, ownership of some plants, and may grow plants where pruning is not as emphasized; growing one's own food can likely reduce carbon emissions through reduced transportation emissions from shipping food long distances repeatedly. Community garden green roofs may bring more people outside, as well, which could have more wide-ranging impacts. In a broader sense, questions like plant maintenance relate to jobs and economic situations, and if there are less maintenance jobs it is unclear how, among other consequences, longer-term carbon emissions and sequestration could be impacted.

Additional research should be pursued regarding rooftop strength and ability to grow trees. A surprisingly large quantity of trees are located throughout Seattle's rooftops and elevated courtyards. The psychological implications of an elevated urban forest are vast. Figure X shows a couple of examples of rooftop trees in Seattle.

Figure 35

Rooftop Trees in Seattle

Note. Photos taken by author.

There are many urban form and design considerations for green roofs and elevated courtyards. Though not usually a primary design consideration, there are numerous designs and conditions which can increase or decrease environmental influences and consequent carbon sequestration.

Chapter 6: Conclusion

Natural carbon sequestration is an important and fundamental method of reducing atmospheric carbon dioxide at a time when its concentration is continuously increasing. Vegetation is central to sequestering CO_2 from the air. Additionally, buildings take up massive amounts of space, and much of their roof space is unused aside from roofing materials and sometimes heating/ventilation/air conditioning. Implementing vegetation onto rooftops and other building spaces across these wide areas and throughout cities like Seattle have clear potential for sequestering CO_2. However, research on carbon sequestration in green roofs is still young, as is mapping and analyzing Seattle's green roofs, and analysis of carbon sequestration on green roofs in Seattle has been essentially non-existent. This thesis provides an updated and detailed map of green roofs as well as elevated green courtyards for much of Seattle, categorized into different vegetative intensities: extensive, semi-intensive, and intensive. There are also estimations for green roofs and elevated green courtyards in areas of the city not yet mapped. Data is organized regarding land use and neighborhood patterns. Additionally, this thesis brings together a large collection of green roof carbon sequestration studies and related research, in order to have a broad evidence-based set of data and information to estimate carbon sequestration rates for the three common green roof intensities. Using that information, this thesis becomes the first attempt to quantify Seattle's current carbon sequestration on buildings.

It is found that 1,527 buildings in Seattle had green roofs and/or elevated green courtyards, according to direct observation of imagery and mapping. Those buildings contain 1,532,967 sq ft of green roofs (subdivided into extensive, semi-intensive, and intensive), and 678,658 sq ft of elevated green courtyards (subdivided into extensive, semi-intensive, and intensive). This leads to a total of 2,211,625 sq ft of green roofs and elevated green courtyards, or 0.079 sq miles. Taking into account the estimated sequestration rates for extensive, semi-intensive, and intensive building vegetation, there was a total of 1,819,517 kg CO_2 sequestered per year, or 1,820 metric tons of CO_2 per year, by Seattle's green roofs and elevated courtyards. There is also an estimated 345,408 sq ft of unaccounted green roofs and 112,234 sq ft of unaccounted elevated green courtyards. This leads to a total of 457,642 sq ft, or 0.016 sq miles. These sequester approximately 331,562 kg of CO_2 per year, or close to 332 metric tons per year. Combining accounted and unaccounted green roofs and elevated green courtyards, there are approximately 2,669,267 sq. ft., or 0.096 sq. miles, and 2,151,079 kg, or 2,151 metric tons sequestered per year.

This thesis and its process have brought forth many ideas for future research that could improve green roof and elevated green courtyard carbon sequestration estimates in Seattle, whether through direct sequestration experiments, improved mapping techniques, or other ideas to better understand the relationship between Seattle's buildings and carbon dioxide.

It is clear that direct green roof and elevated green courtyard experiments need to take place in Seattle in order to have more accurate estimates of kg CO_2 m^{-2} sequestered over time- this means having data on climate, plants, trees, soil, maintenance techniques, buildings, and urban effects directly useful for Seattle. Additionally, the discrepancy between tree sequestration rates and green roof sequestration rates should be examined; this means better understanding the implications of direct plant matter and soil measurement, gas exchange, or biomass/growth equations for resulting sequestration rates. Theoretically, an option for trees could be to plant a large collection of them on a green roof, and cut one down each year for many years and directly measure the carbon content, and see how this compares to the biomass/growth equations (the trees that are cut down could be used for materials which allows them to store the carbon in a long-term way rather than decomposing). Thinking ahead by examining plants that will do well as the climate in Seattle changes is also a worthy research pursuit.

Experiments to better understand carbon sequestration in Seattle should also take into account building designs. Some elevated courtyards may be structurally stronger than green roofs; if they are on top of parking, for example, and so may be able to hold larger trees or other plants. The height of vegetation, whether elevated by 5 ft, 20 ft, 40 ft, or 400 ft, could also have an impact on sequestration rates. Additionally, the structures/designs and materials of buildings can impact the rate of direct sun exposure, sun reflections, shadows, wind, precipitation, and temperature- these factors can absolutely affect sequestration rates. Large street trees overhanging onto elevated courtyards can also impact these factors.

More accurately mapping out the green roofs and elevated courtyards in Seattle could entail higher-resolution aerial and satellite imagery in addition to more street and building imagery. To deal with any resulting challenges from aerial/satellite imagery, such as shadows, building visits could be performed. Technically, visiting all buildings with elevated vegetation, in addition to analyzing all Seattle Green Factor and Landscaping Plan sheets for those with formally-planted vegetation, would be best as specific species, sizes, soil, and microclimatic conditions could be examined. This strategy would be best if done periodically. Of course, there are logistical challenges to performing this type of detailed analysis. One idea could be for building owners to submit periodic photographs of rooftop/elevated courtyard vegetation, though this would also likely have logistical challenges.

Whatever methods are chosen to improve sequestration measurements and mapping, this thesis has data which can be utilized: sequestration rates can be updated, vegetative and building categories could be added, and the map can be edited and built upon.

There are some considerations regarding carbon sequestration and emissions that were not central to this thesis but which would allow for more accurate net carbon impacts of green roofs and elevated vegetation. One example, as was discussed, was determining whether organic or inorganic fertilizer would be best for these plants. Organic fertilizer would increase decomposition on the green roofs/courtyards and would need to be transported to the sites, while inorganic fertilizers would not lead to decomposition but would not only need to be transported but be produced (Smith & Smith, 2015). It is unclear which type of fertilizing method would lead to lower CO_2 emissions. Similarly, it is important to consider a lifecycle emissions assessment to ensure the sequestration of green roofs outweighs the emissions gone into their development (for a review, see Shafique et al., 2020). There is also a large amount of research demonstrating green roofs' ability to decrease energy costs for buildings compared to many other roofs, as well as reduce the Urban Heat Island effect, both of which can indirectly reduce CO_2 emissions- these factors should be studied in Seattle (for reviews, see Manso et al., 2021; Shafique et al., 2018). Additionally, combining solar panels with green roofs has been shown to increase solar panel efficiency compared to those without green roofs (for reviews, see Manso et al., 2021; Shafique, Luo, et al., 2020). At the same time, the physical aspects of solar panels being on roofs can improve green roofs' vegetative growth and biodiversity (Jahanfar et al., 2019; Nash et al., 2016). As solar panels can be applied in Seattle, it would be fruitful to study these interactions and what they mean for CO_2 sequestration as well as overall lifecycle emissions.

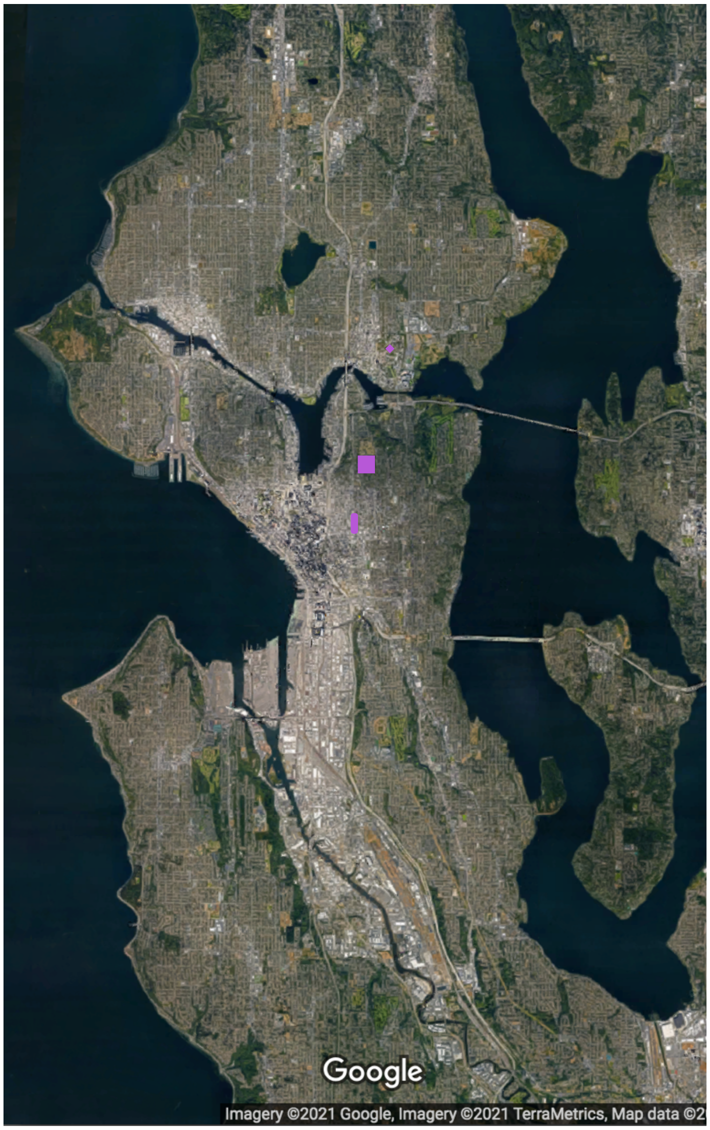
Lastly, there are numerous policy studies that could be done. If green roofs and elevated courtyards are mapped across years, there can be analyses of before and after policy implementations, like before and after the SGF went into effect. This should be compared with nearby cities like Portland and Vancouver over the same time periods to help determine how much policies may affect the amount of green roof implementation versus larger green roof implementation that may have happened independently of policies. Additionally, green roof intensivities can be examined across cities. Not only could these allow for greater understanding of green roof implementation and sequestration, these investigations could also provide new ideas and insights into green roof implementations which could lead to greater sequestration.

It is hoped that this thesis will provide a strong foundation for moving forward on these and other topics in ways that can lead to increased CO_2 sequestration, reduced CO_2 emissions, and other benefits from green roofs and elevated green courtyards in Seattle and beyond.

Clearly, there has been a lot of green roof/elevated green courtyard development in Seattle. However, the amount that has been created is just a miniscule fraction of what could be implemented. The total area of all green roofs and elevated green courtyards found in this study, including unaccounted, is approximately equivalent to the areas of Volunteer Park and Cal Anderson Park in Capitol Hill, plus half of the UW quad or the footprint of about 96 Gould Halls. The areas of Volunteer Park, Cal Anderson Park, and half of the UW quad are marked in Figure 36.

Figure 36

Local Greenspace in Purple to Demonstrate Estimated Green Roof/Elevated Courtyard Space Currently Existing in Seattle



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Note. From Google Maps, 2021, Copyright by Google, 2021.

As development in Seattle continues, efforts should be put forth to not only reduce CO_2 emissions but to increase CO_2 sequestration. Green roofs and elevated green roofs, when implemented thoughtfully and expanded widely, have potential to, among many other benefits, become an important tool in helping Seattle reach net-zero carbon emissions.

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Appendix:

A.1: Attempting to Determine Sequestration Rates of Trees

There does not appear to be directly available data for sequestration rates for trees in Seattle, rooftop or not. Therefore, an approximation will be sought based on tangential information available, including modeling.

Firstly, a tool called i-Tree was utilized; i-Tree is described on its website as "…a state-of-the-art, peer-reviewed software suite from the USDA [United States Department of Agriculture] Forest Service that provides urban and rural forestry analysis and benefits assessment tools" (i-Tree, 2020, top of page). Specifically, the i-Tree Planting Calculator v2.1.2 tool was used- this tool "…is designed to help…estimate the long-term environmental benefits from a tree planting project. The focus is on greenhouse gases, but many co-benefits are included" (i-Tree Planting, n.d., top of page).

The tool works by inputting a particular city in the United States, contextual project parameters, and conditions of particular species of trees to be planted. Then a calculation is processed regarding CO_2 sequestration. There are other parameters and calculations, but these are the relevant inputs and output.

The list of trees were examined for familiarity and potential suitability for both Seattle and green roofs or elevated courtyards. Two species were selected which exist in Seattle and were seen and/or deemed feasible for elevated courtyards and green roofs. A main consideration for green roof feasibility is size- as will be discussed further, trees were deemed feasible for green roofs if they are less than 30 ft tall at maturity. The trees chosen i-Tree Planting's list were

(1) the Southern Magnolia (*Magnolia Grandiflora*) and the Japanese Maple (*Acer Palmatum*). The particular cultivars of Southern Magnolia in Seattle do not grow as tall as a typical Southern Magnolia one would find in the southern United States- rather than 80 feet in height, the *Magnolia Grandiflora 'Victoria'* cultivar, for example, grows up to 30 feet tall (City of Seattle, n.d.; Magnolia Garden Center, n.d.; Ness & Niemiera, 2009; North Carolina Extension Gardener Plant Toolbox, n.d.; Williams, Sibley, Gilliam, & Creech, 2002).

Using i-Tree Planting to estimate carbon sequestration of Southern Magnolia and Japanese Maple trees in Seattle required inputting a Diameter of the trunk at Breast Height (DBH) parameter for these trees. The DBH is found by taking the circumference (C) of a tree trunk at ~4.5 ft from the ground, and then determining the trunk's Diameter (D) using the equation:

$$D = \frac{C}{\pi}$$

which is reworked from the common equation for determining the circumference of a circle:

$$C = \pi D$$

with the assumption that the portion of the tree trunk being measured is a perfect circle.

A.1.1: Gathering and Testing Data on Local Trees

In order to input the DBH parameter on i-Tree Planting, a field exploration was performed to find existing examples of Japanese Maple and Southern Magnolia trees on the ground level. Species identities were confirmed via a mobile app called "Seek" (iNaturalist, 2021) or by a City of Seattle GIS map of street trees (Trees for Seattle, n.d.), though the exact cultivars are uncertain.

After finding relatively small Japanese Maple trees, a larger one was found for which measuring the circumference was relatively easy. An image is in the figure below.

A Japanese Maple Tree in Seattle

Note. Photo by the author.

The circumference at breast height of this Japanese Maple tree was measured to be approximately 6” (approximately the minimum tree circumference included in Hutyra et al.’s (2011) field analysis). This circumference was used to determine the DBH, which was approximately 1.9”. Later, the approximate length and width were measured in order to allow for calculation the area of the tree so that the amount of CO_2 sequestered per square meter could be calculated; this way the data would be comparable to the green roof sequestration data. The tree measured 9’ by 6’- this was later converted to meters. Google Maps and King County iMap suggest that this tree has been in this location (11th Ave E and E Thomas St in Seattle) since at least October 2007, what appears to be 2005, and possibly earlier (Google, 2021; King County/Aerials Express, n.d.).

A relatively new/small Southern Magnolia was found near 12th Ave E and E Thomas St in Seattle- Google Maps Street View indicates that the tree was planted at some point between May 2018 and May 2019 (Google, 2021). An image of the tree is in the figure below.

A Small Southern Magnolia Tree in Seattle

Note. Photo by the author.

The circumference at breast height of this Southern Magnolia tree was measured to be approximately 4”. This was used to determine the DBH, which was approximately 1.3”. The length x width was approximately 5’ by 4’.

Later, a larger Southern Magnolia was sought in order to provide a different carbon sequestration estimate. This tree, found on E Howell St between 12th Ave and 13th Ave, is shown below.

A Larger Southern Magnolia Tree in Seattle

Note. Photo by the author.

The circumference of this tree's trunk at breast height was 18 inches, meaning a DBH of about 5.7 inches. The tree was measured on King County iMap to have a length x width of about

10 ft by 12 ft (King County/Aerials Express, n.d.). Based on Google Maps and King County iMap, this tree was planted here some time between late 2007 and some time in 2009. (Google, 2021; King County/Aerials Express, n.d.).

Even larger Southern Magnolias were found, but these provide sufficient data to serve the purpose.

A.1.2: i-Tree Planting Analysis

Using i-Tree Planting, the analysis of the aforementioned Japanese Maple and Southern Magnolias included the following inputs:

For Location:

State: Washington

County: King

City: Seattle

For Parameters:

Electricity Emissions Factor: [Not relevant for sequestration].

Fuel Emissions Factor: [Not relevant for sequestration].

Years for the Project: 1 (will also try 2)

Tree Mortality over Project Lifetime: Does not matter for the 1-year analyses because when the analysis is set for only 1 year, the tree mortality rate has no impact on sequestration. For the 2-years analyses, 7% will be used for the newer Magnolia, and 3% will be used for the more-settled Japanese Maple and larger Southern Magnolia (based on a holistic consideration of the literature review on urban tree mortality rates by Hilbert, Roman, Koeser, Vogt, and van Doorn (2019)).

For Trees:

Species: Southern Magnolia or Japanese Maple

DBH [Diameter at Breast Height] in inches at time of planting: 1.9 inches for the Japanese Maple, 1.3 inches for the smaller Southern Magnolia, and 5.7 inches for the larger Southern Magnolia.

All four inputs for "Building Information": [Not relevant for sequestration]

Tree Condition: Good (did not want to overestimate and say "Excellent")

Exposure to Sunlight: Full Sun (on average, rooftop trees and other elevated trees likely get more sun than ground-level trees)

Number of Trees: 1

Then the CO_2 sequestration is calculated using a type of growth equation described in Chapter 2 (McPherson et al., 2016).

The cultivar of Southern Magnolia in Seattle reaches a smaller maximum height (30-40 feet) compared to a larger cultivar (likely represented in i-Tree Planting, given heights measured in the *Urban Tree Database and Allometric Equations* technical report which informs i-Tree Planting), so how may the growth rate differ between these different varieties per year?

A series of calculations were performed involving the diameter of a different part of the young Southern Magnolia (the caliper) based on guidance from the *American Standard for Nursery Stock*, different cultivars of Southern Magnolias found in Williams et al.'s (2002) study, and growth equations from the *Urban Tree Database and Allometric Equations* technical report (McPherson et al., 2016; Quinn, 2014). Put simply, if i-Tree is using a large, classic Southern Magnolia in its calculations, the sequestration calculation for Seattle's Magnolia could be 1/3 to 2/3 as much as reported, even taking into consideration the climate calculations included in i-Tree Planting's model. However, this could be incorrect, and the location specification could potentially adjust the cultivar or the growth conditions appropriately. For simplicity, we can assume no adjustments are required.

Less attention was given to Japanese Maples regarding height differences because Japanese Maples generally do not grow more than 25 ft in height (Ness & Niemiera, 2018).

The CO_2 sequestration results for the:

-Japanese Maple with a 1.9-inch DBH after 1 year was 5.2 kg CO_2.

-Japanese Maple with a 1.9-inch DBH after 2 years was 11.6 kg CO_2, meaning 6.4 kg CO_2 sequestered the second year and an average of 5.8 kg CO_2 per year.

-Southern Magnolia with a 1.3-inch DBH after 1 year was 3.5 kg CO_2.

-Southern Magnolia with a 1.3-inch DBH after 2 years was 8.6 kg CO_2, meaning 5.1 kg CO_2 sequestered the second year and an average of 4.3 kg CO_2 per year.

-Southern Magnolia with a 5.7-inch DBH after 1 year was 22.9 kg CO_2.

-Southern Magnolia with a 5.7-inch DBH after 2 years was 48.2 kg CO_2, meaning 25.3 kg CO_2 sequestered the second year and an average of 24.1 kg CO_2 per year.

Knowing the approximate length and width of the trees, we can estimate the area they cover in square meters (sq m), so the kg CO_2 per sq m can be determined. Following the same method as Williams et al. (2002) for determining the canopy width, the north-south and east-west measurements of length/width were added together and divided by 2. Then that will be divided by 2 to find the radius (r), and then, assuming the trees are circles, can use the formula for finding the area (A) of a circle:

$$A = \pi r^2$$

The changes in length/width of the trees over time can be approximated by observations on King County iMap for the larger Southern Magnolia, which is visible over several years. In 2015, the area was ~6.6 sq m. In 2017, 10.1 sq m. In 2019, 10.5 sq m. These may not be totally accurate. Let's just assume since this is a relatively young tree there is some growth linearity. Since none of these trees are likely very old, and for simplicity, we can apply this to them, as well. 3.9 sq m/ 4 years = ~ 1 sq m per year growth in area.

Calculating out all the areas for the Japanese Maple and the Magnolias from the field/iMap measurements, converting them into square meters, and dividing the kg CO_2 per sq m, the estimated sequestration rates are as follows below:

Estimated Kilograms of Carbon Dioxide Sequestered by Local Trees

Tree	**Kg CO_2 m^{-2} after 1 year**	**Kg CO_2 m^{-2} after 2 years**
Japanese Maple	1.02	1.90
Smaller Southern Magnolia	1.40	2.46
Larger Southern Magnolia	1.99	3.86

Note. Estimates from a combination of: author measurements in 2021; King County/Aerials Express (n.d.); *Planting Report/Project Report - i-Tree Planting Calculator v2.1.2*, n.d.). Credit goes to i-Tree Cooperative for the i-Tree Planting Calculator.

Here is the illustration of the issue- these numbers are quite small. Several of them are very close to the calculated sequestration rate of Extensive Green Roofs calculated earlier in the Methods section (1.348 kg CO_2 per sq m)! Even if assuming pure carbon growth upwards with no increase in area at all, the maximum sequestration rate would be 5.73 kg CO_2 per sq m (for the Small Southern Magnolia)- less than half the calculated sequestration rate of the Semi-Intensive Green Roofs calculated earlier in the Methods section. This raises questions about the accuracy of this data, the green roof sequestration data, or both. Perhaps this is just an incorrect way of analyzing tree sequestration per unit area. For example, maybe the true 'area' of trees is that which takes up space on the ground and prevents other vegetation from growing there. If the trunk is technically the only part of the tree taking up ground space, and varieties of vegetation can grow underneath the canopy, then the amount of carbon sequestered per square meters of tree trunk would be huge. For example, if the large Southern Magnolia's area was considered just the trunk, that area at the level of the DBH would be 0.01663 sq m. Let's just say the circumference of the trunk is double that at breast height. That area at the ground level would then be 0.0665 sq m- the sequestration rate in 1 year (assuming no trunk growth for simplicity) would be 344.36 kg CO_2 per sq m. Further, the extra space for vegetation under the canopy could allow for even more sequestration of CO_2 per sq m. However, there are of course limits to what can be grown underneath a tree's canopy, particularly if the canopy hangs low. Looking ahead toward methods for mapping Seattle's green roof vegetation, it would be quite challenging to estimate and draw out the area of every trunk beneath every tree, rather than simply draw over the tree canopies and include that entire area. McPherson et al. (2016) do describe remote sensing which can estimate the DBH from the crown, but this is not a logistically feasible option at the moment. Also, the Intensive sequestration category, if including a tree, would still classify as Intensive whether or not there is vegetation underneath, but it would be difficult or impossible to tell from aerial imagery how high up trees' canopies are off the ground and if/where it is possible to grow vegetation underneath them; if the canopy prevents anything from growing underneath, then the tree functionally takes up that entire area, which lowers the sequestration rate to numbers similar to the 1 – 4 kg/sq m shown above, for example. It can also be true that even when there technically is space available for vegetation underneath canopies, that space is not used for any vegetation planting, again functionally meaning that the tree takes up that entire area. See the photos above for a variety of conditions underneath the trees.

Plants from Tenneson's (2014) dissertation were also examined with the same general conditions as the others. Assuming pure upward growth (i.e., no increase in area), a Northern White Cedar with a 10 DBH sequestered 4.9 kg CO_2 after 1 year. A Vine Maple with a 10 cm DBH sequestered 0.4 kg CO_2. A Vine Maple with a 40 cm DBH sequestered 2.5 kg CO_2. A Japanese Maple with a 10 cm DBH sequestered 12.4 kg CO_2. A Japanese Maple with a 50 cm DBH somehow sequestered only 2.0 kg CO_2- perhaps this is a characteristic of Japanese Maples once the DBH reaches a certain size. Though these are the sequestration rates for 1 year, it is unclear how large an area they take up; however, even if they took up only 0.5 sq m, only one of these (the Japanese Maple with a 10 cm DBH) would match the median Intensive sequestration calculation for green roofs, and given that the Japanese Maple observed in Seattle had a DBH of less than half of that took up about a 2.74 m by 1.83 m area, this is highly unlikely ("Planting Report/Project Report - i-Tree Planting Calculator v2.1.2", n.d.).

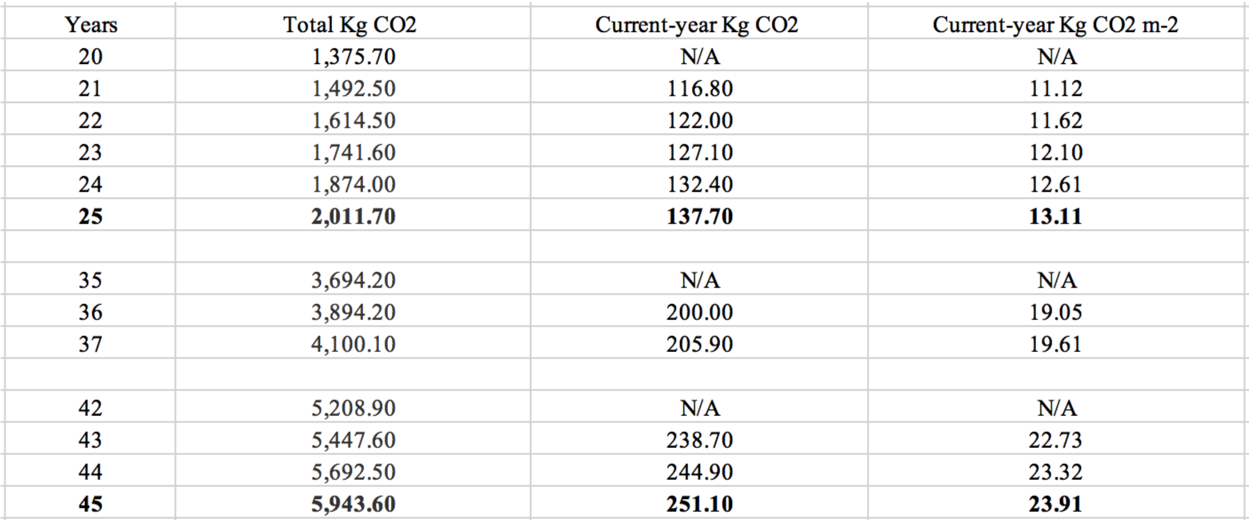
Calculations could vary if belowground biomass and soil are taken into account if they are not already. McPherson et al. (2016), citing Husch et al. (2003), Tritton & Hornbeck (1982), and Wenger (1984), say to multiply dry-weight biomass by 1.28 to account for belowground biomass. It turns out that i-Tree does include belowground biomass sequestration, does not include soil sequestration, and includes leaf carbon for evergreen but not deciduous trees (D. Nowak, personal communication, May 13, 2021).

As the 2-year versions indicate (and the trend can be stronger over longer time periods), sequestration often increases significantly over time. As shown in growth curves above, this can carry on in a greater-than-linear fashion for many years, or can plateau. Carrying out longer-term versions of the type of modeling utilized above, the Southern Magnolias continues to increase carbon content in a greater-than-linear fashion over time, while the slowly-plateauing pattern across time, seen in some of the Sweetgum examples in Figure 10, is similar to the pattern shown with increasing DBH in Japanese Maples, per i-Tree Planting ("Planting Report/Project Report - i-Tree Planting Calculator v2.1.2", n.d.). This is an important consideration for sequestration; the green roof sequestration experiments above are often for relatively short periods of time, making it difficult to determine their sequestration trajectories. The upcoming sequestration estimation for Seattle will thus only be a snapshot and likely an underestimation, however it is still a question of exactly how trees on buildings and trees on the ground may differ regarding sequestration amounts; David Nowak, an author cited in this thesis who currently works for the U.S. Forest Service, said that although some aspects of i-Tree Planting are meant specifically for ground-level trees, i-Tree Planting should be able to provide an acceptable estimation for carbon sequestration of woody rooftop vegetation (D. Nowak, personal communication, February 1, 2021).

One consideration is that relatively large trees on roofs could sequester more significant carbon. Ciecko et al. (2012) and Tenneson (2014) both consider small trees as being less than 30 feet tall at maturity. This may be fairly close to an upper limit for rooftop trees, though it would depend on structural support. The larger magnolia tree the author measured (with the 5.7 inch DBH) appears to be 21 ft tall on Google Earth (Google, n.d.). If all rooftop trees were 30 ft, that could certainly be more significant, although it would also depend on the area they take up and what that means for the amount of carbon sequestered per square meter.

To carry out these analyses further, an examination was performed on i-Tree Planting using the larger magnolia tree (with the 5.7 inch DBH). The aforementioned parameters were entered, except for the number of years. Long-term analyses were performed to determine the extent of the discrepancy between the sequestration rate of a sizeable tree on i-Tree Planting and the median sequestration rates of green roofs of varying intensivities (appearing in Table 3 based on studies examined in Section 2.2.1). The following analysis shows how many years the larger magnolia tree would need to live in order to surpass the kg CO^2 m^{-2} per year of semi-intensive and intensive green roofs, assuming zero expansion in canopy width (which is extremely unlikely given a reasonably healthy tree without particular pruning activities).

Amount and Rate of Southern Magnolia Carbon Sequestration in Particular Years



Years	Total Kg CO2	Current-year Kg CO2	Current-year Kg CO2 m-2
20	1,375.70	N/A	N/A
21	1,492.50	116.80	11.12
22	1,614.50	122.00	11.62
23	1,741.60	127.10	12.10
24	1,874.00	132.40	12.61
25	**2,011.70**	**137.70**	**13.11**
35	3,694.20	N/A	N/A
36	3,894.20	200.00	19.05
37	4,100.10	205.90	19.61
42	5,208.90	N/A	N/A
43	5,447.60	238.70	22.73
44	5,692.50	244.90	23.32
45	**5,943.60**	**251.10**	**23.91**

Note. Parameters are the same as earlier analysis, except for number of years. Years 20, 35, and 42 have “N/A” for current-year sequestration because data was not explored for the year immediately prior to each of those years, meaning the amount sequestered beyond the year before is unknown. Years 25 and 45 are bolded because they are the years that sequestration rate per square meter surpassed that of the median sequestration rates of semi-intensive and intensive green roofs, respectively, included in Chapter 3. Used *Planting Report/Project Report - i-Tree Planting Calculator v2.1.3*, n.d.), with engine v0.5.3 (APIv2) and database v11.1.14. Credit goes to i-Tree Cooperative for the i-Tree Planting Calculator.

This analysis shows that, assuming zero expansion in width of the tree canopy, it would take the larger southern magnolia tree 25 years to surpass the median annual sequestration rate of included semi-intensive green roofs in this thesis, and it would take 45 years to surpass the media annual sequestration rate of the included intensive green roofs. Given that this does include belowground biomass sequestration (not including soil), this significant discrepancy is surprising. Perhaps there are measurement or calculation issues, or details regarding soil and soil depth that need to be elucidated for tree sequestration estimates. Additional analysis showed a sequestration peak between year 62 and year 81; the sequestration rate declined after year 81. This is because i-Tree Planting includes tree respiration and is thus a measure of Net Primary Productivity at the individual tree level (D. Nowak, personal communication, May 13, 2021).

Ultimately, the relatively low sequestration rates found via i-Tree Planting, particularly after the thesis author's possibly misguided attempts at dividing by the area of the tree crown, in contrast to the relatively high sequestration rates of far less intensive green roofs, in addition to uncertainties of vegetation beneath trees when using aerial photos for green roof mapping, as well as research showing heavily forested pacific northwest forests having a Net Ecosystem Productivity of 0.42 – 0.72 kg CO^2 m^{-2} per year (significantly less than all green roof types which typically account for Net Ecosystem Productivity) and a Net Primary Productivity of 2.5 – 3.1 kg CO^2 m^{-2} (significantly less than semi-intensive and intensive green roofs even without the forest accounting for heterotrophic respiration), all inform the decision to forgo the inclusion of this tool at this moment.

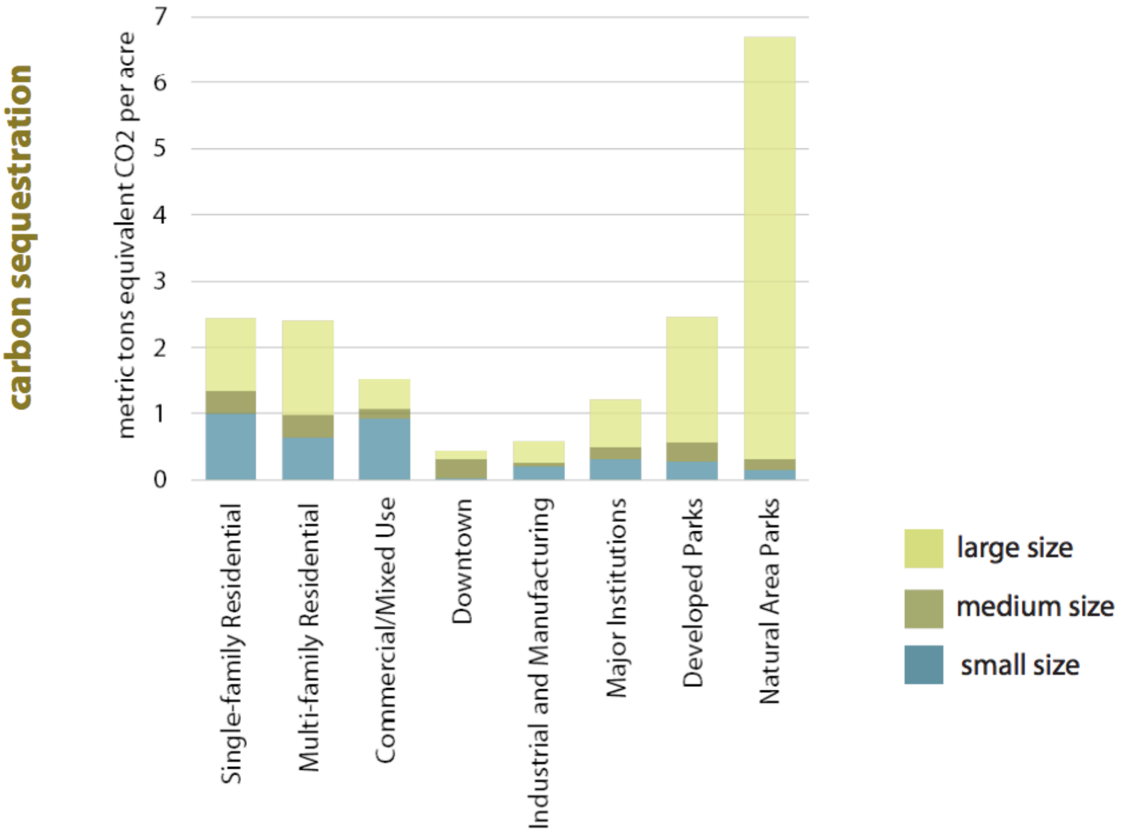
A.1.3: Attempting to Estimate Tree Sequestration Rates via Seattle's Forest Ecosystem Values Report

A 2012 report sought to quantify the characteristics and impacts of Seattle's urban forest, and provided the possibility for deducing carbon sequestration of trees (Ciecko et al., 2012).

Using various bar charts and other data in the document, an attempt was made to determine a CO_2 sequestration rate for small trees (i.e., trees that will be small at maturity). The process went as follows:

It is stated that there are ~4,100,000 trees and tree-like shrubs in Seattle. Approximately 36 tons of CO_2-equivalent are stored per acre, and 2.6 tons are sequestered per acre. This data is broken up in a bar chart into different zones and different tree sizes, as shown below:

Carbon Sequestration in Seattle by Different Land Uses with Size at Maturity of Trees/Tree-like Shrubs



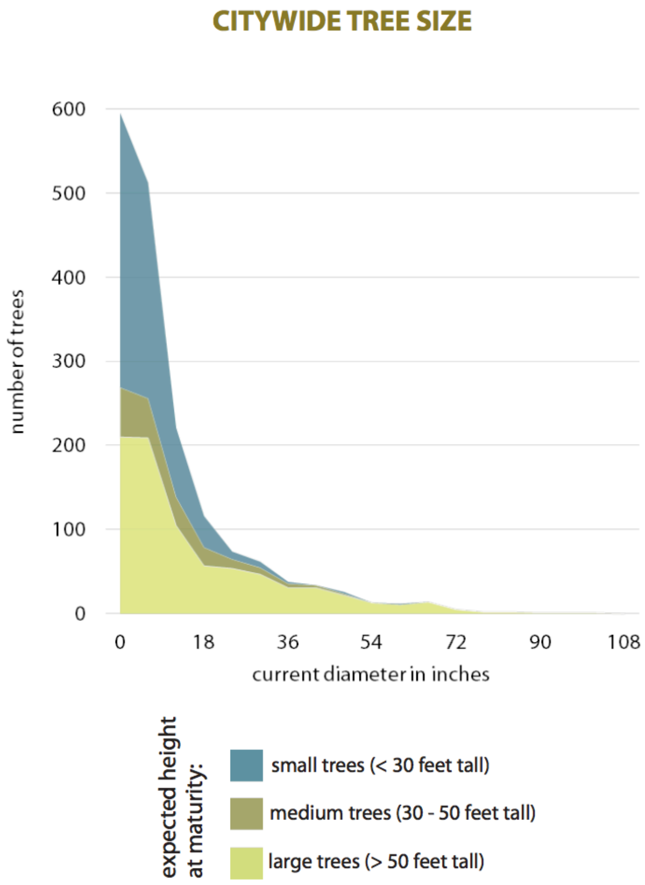
Note. Small trees are defined elsewhere as being less than 30’ tall at maturity- those are the portions of the bar in blue. These are the trees whose information could be useful for green roofs. From *Seattle’s Forest Ecosystem Values: Analysis of the Structure, Function, and Economic Benefits*, by Ciecko et al., 2012, (https://forterra.org/wp-content/uploads/2015/06/Seattles_Forest_Ecosystem_Values_Report.pdf). Copyright information unavailable/unclear.

There was ambiguity as to whether this is the amount sequestered per acre of trees within the different land uses, or the amount sequestered per acre of a given land use. Other information in the document suggests it is the latter- the amount sequestered per acre of a given land use. The document states that ~141,000 tons of CO_2 were sequestered in 2011 across the whole city (Ciecko et al., 2012). 141,000 tons divided by 2.6 tons sequestered per acre is 54,230.77 acres. There are 640 acres in a square mile ("Convert square miles to acres," n.d.). This means that the city land is ~84.74 sq miles. The document does not state how many square miles are in the city to confirm this, although it does give the percentage of total city land area devoted to different land uses, which will be important later. The City of Seattle gives different numbers for the city's land area: the City Municipal Archives states that there are 88.4997 sq miles of land in the city, and that the World Almanac states that there are 84 sq miles (Seattle Municipal Archives, n.d.). However, the Office of Planning and Community Development (OPCD) states that there are 83 square miles, or 53,113 acres (OPCD, n.d.). 84.74 sq miles will be the number used moving forward.

With the basics confirmed, an analysis will be started with the carbon sequestration information for the single-family land use (SF). It is shown that approximately 1 ton of CO_2 is sequestered per acre of SF land use (not 1 ton of CO_2 per acre of small trees). The document states that 56% of city land area is SF, which is ~47.45 sq miles of SF. That is 30,368 acres of SF. Small trees in SF thus sequester 30,368 tons of CO_2 in SF zoning. However, the document states elsewhere that ~27% of SF has canopy cover- 8,199 acres. This means that small trees in SF sequester 30,368 metric tons of CO2 within that 8,199 acres. Importantly, however, that canopy cover also contains medium and large trees; this means that SF sequesters 30,368 tons of CO_2 in the fraction of the 8,199 acres that is made up of small trees. How much area do the small trees take up?

This is where an answer becomes increasingly challenging to find. Other data in the document show that there are 1,850,000 trees in the SF, and 47% of those are small trees. That is 869,500 small trees in SF. It is shown elsewhere that 30% of trees in the SF are small (at maturity) and have a DBH greater than 12 inches- 555,000 small trees. 15% of trees in SF zoning are small and have a DBH that is 6-12 inches- 277,500 small trees. 2% of trees in SF zoning are small and have a DBH less than 6 inches- 37,000 small trees. Specifically, a different graph shows how many trees have different sized DBHs, shown below:

Number of Trees in Seattle by Tree DBH with Size at Maturity of Trees



Note. From *Seattle's Forest Ecosystem Values: Analysis of the Structure, Function, and Economic Benefits*, by Ciecko et al., 2012, (https://forterra.org/wp-content/uploads/2015/06/Seattles_Forest_Ecosystem_Values_Report.pdf). Copyright information unavailable/unclear.

Assuming the y-axis was mislabeled (it should be 1,000 times larger), and presuming that the trees labeled at 0 inches means less than 6 inches, it showed that:

Estimated Number of Small Trees (when Mature) in Seattle by Tree DBH

Approximate DBH (inches)	**Approximate Number of Trees**
< 6	590,000
6	515,000
12	225,000
18	115,000
24	75,000
30	65,000
36	40,000
42	35,000
48	30,000
54	20,000
60	20,000
66	22,000
72	0

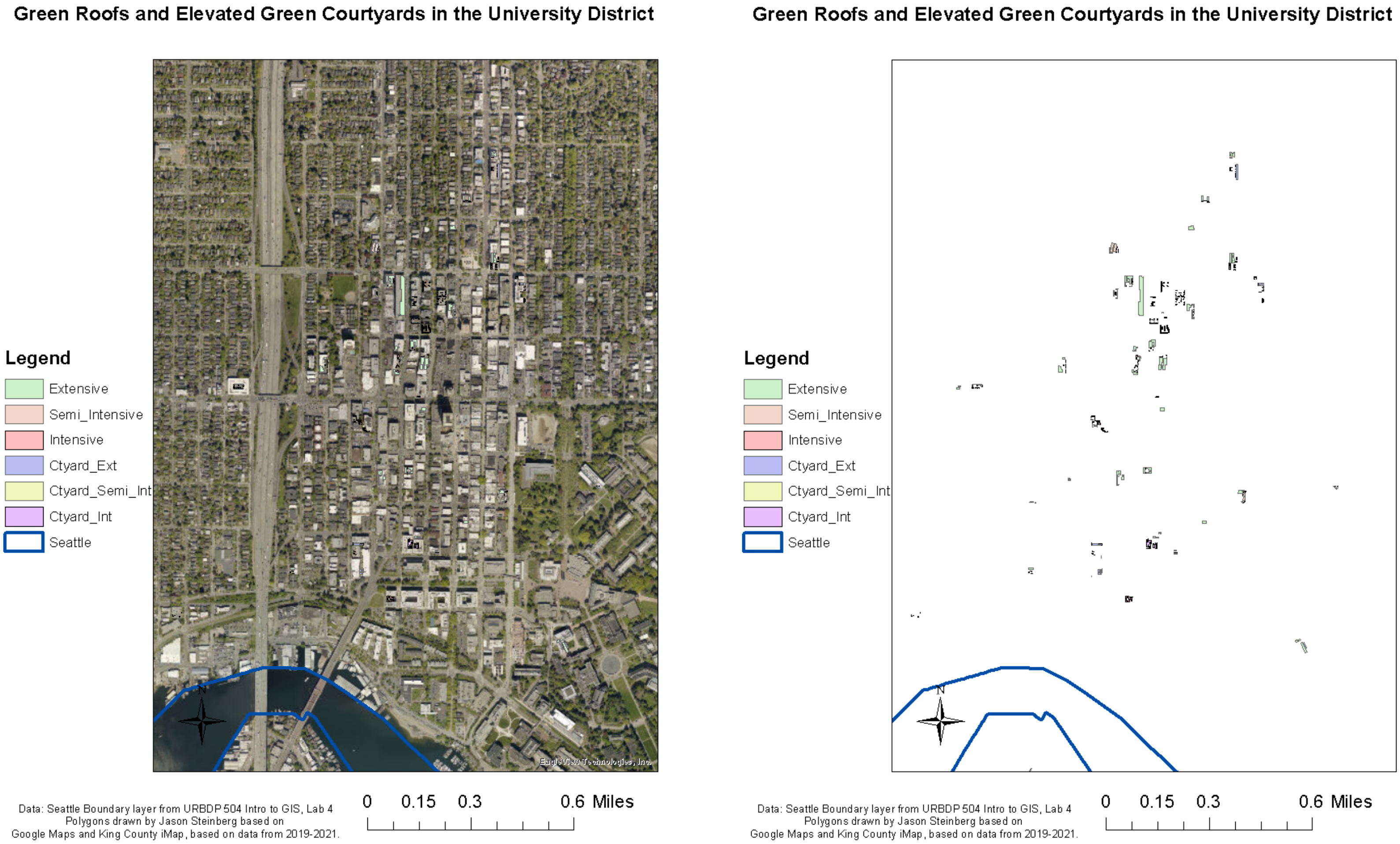
Note. Adapted from From *Seattle's Forest Ecosystem Values: Analysis of the Structure, Function, and Economic Benefits*, by Ciecko et al., 2012, (https://forterra.org/wp-content/uploads/2015/06/Seattles_Forest_Ecosystem_Values_Report.pdf). Copyright information unavailable/unclear.

This is a total of 1,752,000 small trees in Seattle. There are 869,500 small trees in SF, and it is known that 555,000 of them have a DBH greater than 12 inches, 277,500 that have a DBH of 6-12 inches, and 37,000 that have a DBH less than 6 inches. There is no direct data elsewhere in the document that gets more specific than that. Further, knowing a DBH does not guarantee knowledge of a tree's area (McPherson et al. (2016) state, for example, that knowing both the height and DBH of a tree likely gives more accurate results than just knowing the DBH (p. 69)).

Elsewhere, it is shown that 50% of trees in SF are deciduous broadleaf, 15% are evergreen broadleaf, and 35% are evergreen conifer. This information on DBH and tree type could theoretically be used in volume equations for Generic Broadleaf and Generic Conifer trees (McPherson et al., 2016). Then, knowing the volumes, potentially tree areas could be estimated from that. But the general growth equation for broadleaf trees needs a DBH of at least 6 cm, and the growth equation for conifer trees needs a DBH of at least 16 cm (McPherson et al., 2016). Which types of small trees have which sizes of DBH? Where within the 6-inch DBH demarcations should these trees be allocated? It seems too many assumptions and qualifications would need to be made. There is a large index of the tree species which were sampled for this data, but even then, that would not guarantee how many of which broadleaf and evergreen species there were, and how large their specific DBHs would be. Additionally, the calculations would need to be repeated for trees in all the other land uses besides just SF- this is not a feasible process. While this report has plenty of valuable information on Seattle's urban forest, it is not the best source of information for determining the sequestration of small trees per square meter. In reaching out to two of the co-authors, Karis Tenneson, who works in spatial informatics, responded that another format of the sequestration data was not available, but proposed looking at growth equations and cautioned about potential differences in growth rates between trees on the ground and trees on a roof (K. Tenneson, personal communication, April 22, 2021).

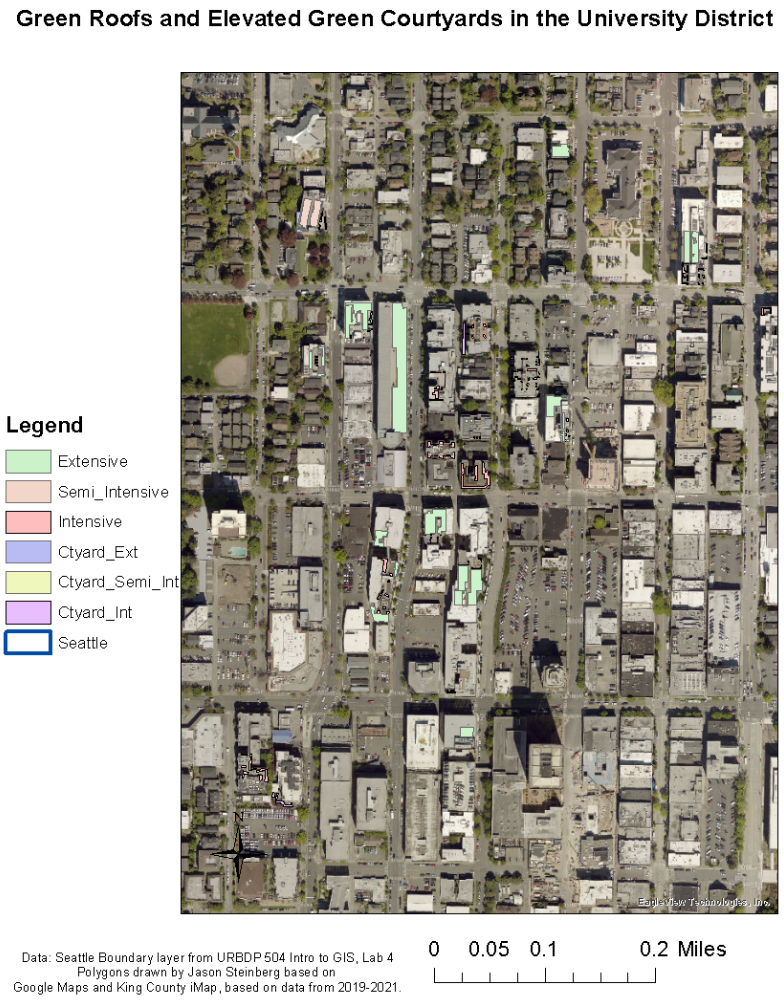
A.2: Example Showing Closer Views of Mapping

The University District Mapped

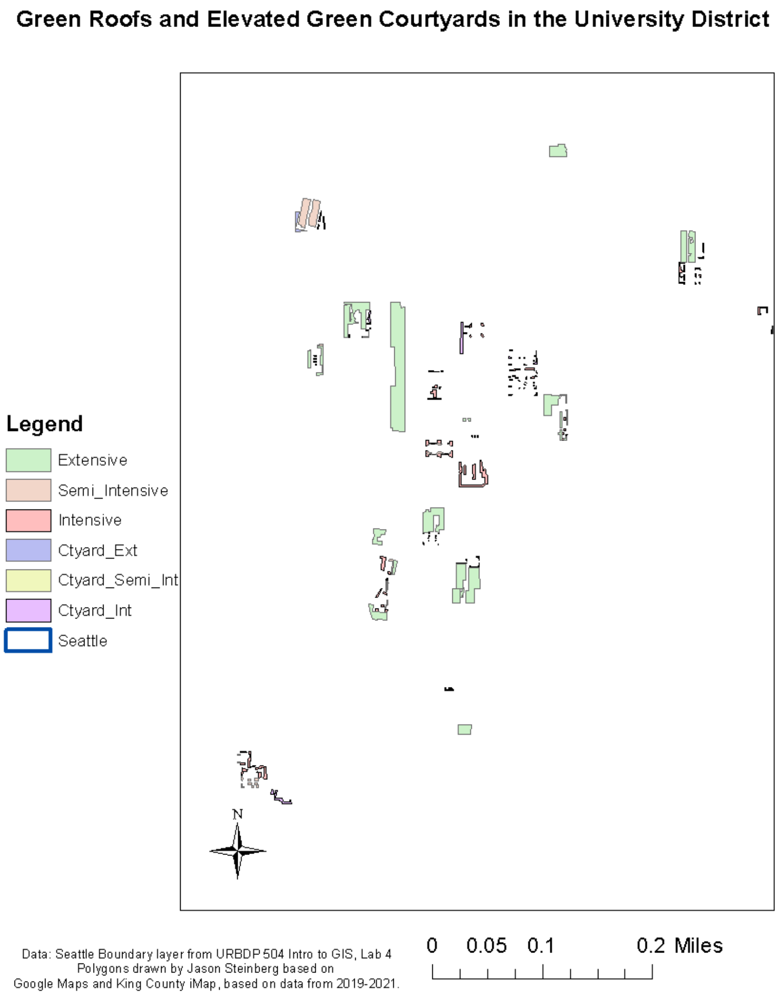


Note. Ctyard_Ext = Extensive Elevated Green Courtyard; Ctyard_Semi-Int = Semi-Intensive Elevated Green Courtyard; Ctyard_Int = Intensive Elevated Green Courtyard

The University District Closer



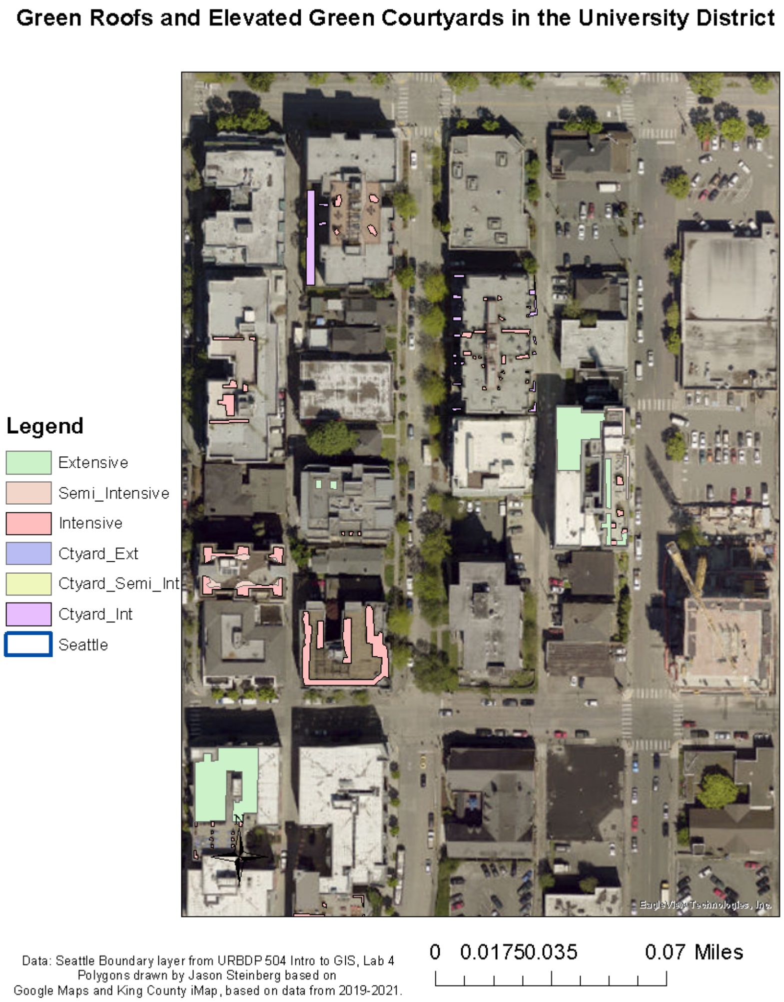
Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4
Polygons drawn by Jason Steinberg based on
Google Maps and King County iMap, based on data from 2019-2021.



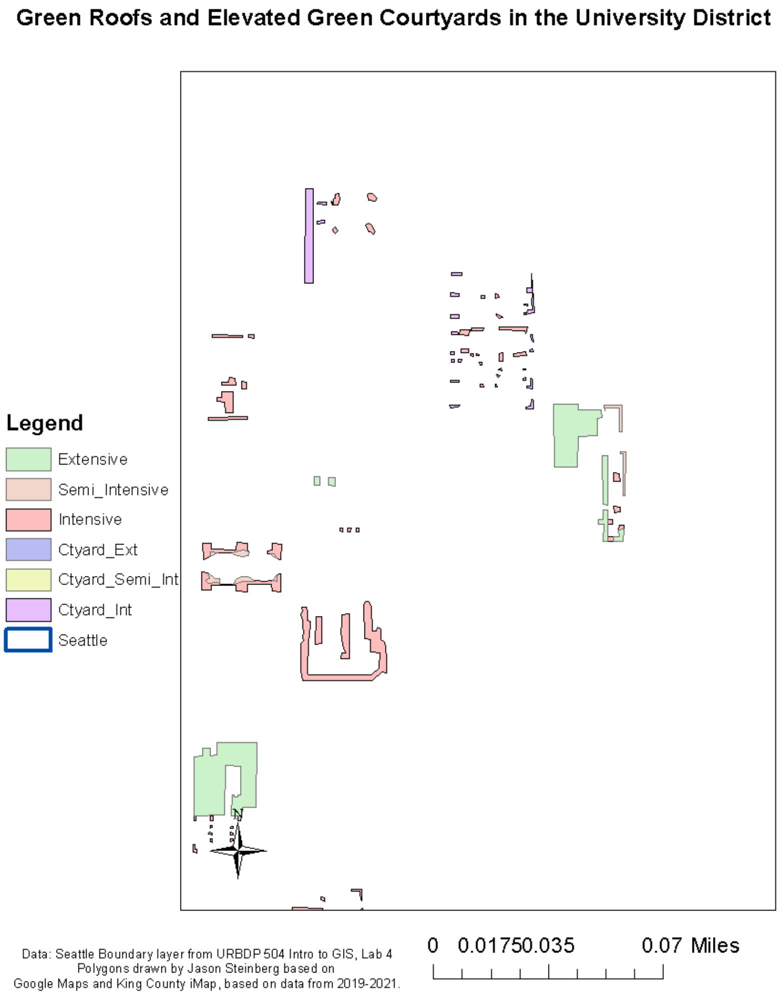
Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4
Polygons drawn by Jason Steinberg based on
Google Maps and King County iMap, based on data from 2019-2021.

Note. Ctyard_Ext = Extensive Elevated Green Courtyard; Ctyard_Semi-Int = Semi-Intensive Elevated Green Courtyard; Ctyard_Int = Intensive Elevated Green Courtyard

The University District Subsection


Green Roofs and Elevated Green Courtyards in the University District

Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4
Polygons drawn by Jason Steinberg based on
Google Maps and King County iMap, based on data from 2019-2021.


Green Roofs and Elevated Green Courtyards in the University District

Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4
Polygons drawn by Jason Steinberg based on
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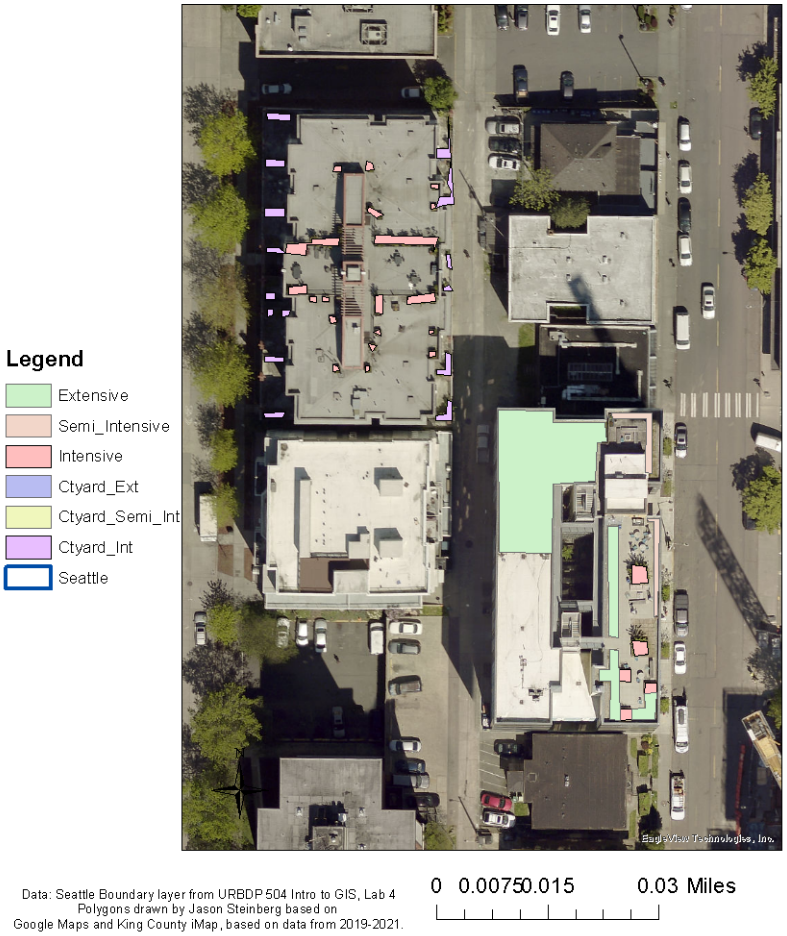
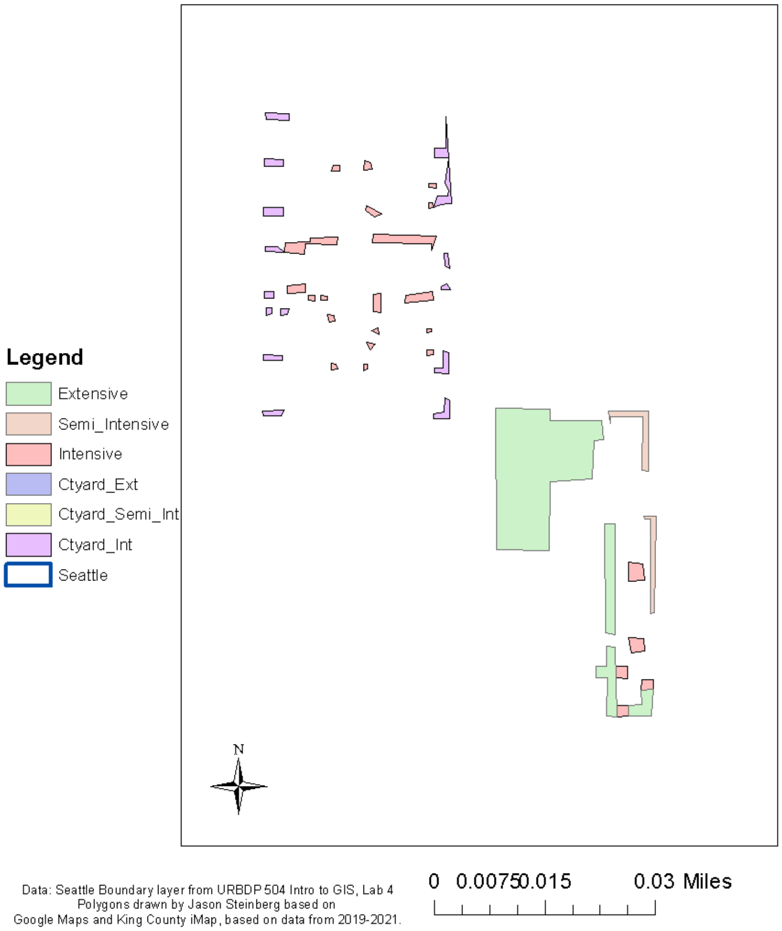
The University District Buildings-Level

Green Roofs and Elevated Green Courtyards in the University District



Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4
Polygons drawn by Jason Steinberg based on
Google Maps and King County iMap, based on data from 2019-2021.

Green Roofs and Elevated Green Courtyards in the University District



Data: Seattle Boundary layer from URBDP 504 Intro to GIS, Lab 4
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