A CITY UNDER THE SEDUMS: ECOSYSTEM SERVICES AND ADOPTION OF VEGETATED ROOFS IN ATLANTA, GEORGIA

by

JAMES SCHULTE

(Under the Direction of Jon Calabria)

ABSTRACT

The city of Atlanta, Georgia is often referred to as the city in the forest because almost half of its area is covered in urban tree canopy. Unfortunately, urbanization is threatening the canopy. I posit if rooftops can offset lost functions from urban canopy loss. Atlanta is surprisingly far behind cities such as Portland, Chicago, and Washington, D.C. when it comes to vegetated roof implementation. Several precedent studies highlight benefits and explore their potential, while projective design calculates the ecosystem services from a typical 20,000 square foot extensive vegetated rooftop and extrapolates results into different adoption rates throughout the city. While vegetated roofs cannot offset the loss of urban trees one for one, they are an excellent option for urban areas to supplement the existing canopy. Future research can use more extensive computer models to gain real results and support the idea of vegetated roof policy for the city of Atlanta.

INDEX WORDS: Atlanta, Green Infrastructure, Landscape Architecture, Urban Tree Canopy, Vegetated Roof, Vegetated Roof Policy

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JAMES SCHULTE

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A CITY UNDER THE SEDUMS: RESEARCH INTO THE ECOSYSTEM SERVICES OF VEGETATED ROOFS

IN ATLANTA, GEORGIA

by

JAMES SCHULTE

Major Professor: Jon Calabria
Committee: Robert A. Vick
David Spooner
Steve Sanchez

Electronic Version Approved:

Ron Walcott
Dean of the Graduate School
The University of Georgia
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CHAPTER 1

INTRODUCTION

In the fall of 2019, I was trying to figure out a topic for my thesis. I wanted something that would be relevant for the current time and culture, while also being of great interest to me. I was considering a few ideas, but nothing seemed to stand out. I was getting frustrated with the lack of a decent topic, when one day I was standing at the printer in the office looking out over the Buckhead skyline on the north edge of Atlanta, Georgia. It was a view that I had seen practically every day for the last five years. To my right was Lenox Square mall and its sea of parking, while straight in front of me were countless buildings with barren rooftops. It was the mix of the two that made me think, “it would be interesting if those roofs were covered in vegetation instead of nothing”. It sure would have made the view more compelling while standing waiting for my documents to come out of the printer. From that thought came the idea for this thesis. I decided that I wanted to explore the potential impact that green roofs, or what this paper will refer to as vegetated roofs, would have on the city of Atlanta, both in terms of offsetting the loss of the urban tree canopy due to commercial development as well as providing ecosystem services for the city as a whole.

Thesis Description

While the goal of this thesis is to research the benefits of vegetated roofs for the city of Atlanta, GA for the two reasons mentioned above, another further goal of the thesis as a whole is to attempt to start a conversation with local government municipalities about the importance of vegetated roof development on commercial projects within their jurisdictions. As this thesis highlights, there are many cities at the forefront of global environmental stewardship which have incentives and policies regarding vegetated roof development. While this thesis does not recommend language for new policies, it does detail adverse effects of urbanization without added green infrastructure. Additionally, it provides evidence of the ecosystem services which vegetated roofs can supply in the hope that governments will examine the potential for policy change.

This thesis covers a range of topics, starting with a literature review that looks at the growth and history of the urban world. Following, issues with climate change and the effects of urban growth on the environment help to illustrate the dangers of reckless growth. Until recently, the main strategy to provide urban greening and environmental benefits to cities was through the planting of trees. As a result, following the section on climate issues is an in-depth look at the history and evolution of urban trees. Lastly, a historical review on vegetated roofs traces their origins from initial implementation to the present.

The sequence of topics aids in explaining that cities are growing, the costs at which they grow, previous remedies, and future ideas for urban greening. The thesis will then shift to examine different trends and economics surrounding vegetated roof policies and incentives around the globe, along with the impact they have on their cities and regions. Multiple international and domestic case studies highlight the ways in which vegetated roofs impact their individual sites. The thesis will then examine, compare, and contrast the economic, environmental, and social benefits that urban trees and vegetated roofs have on their surrounding environments in an effort to determine whether or not vegetated roofs are able to offset the urban tree canopy lost to development.

The second research question within the thesis addresses the specific ecosystem services which vegetated roofs can provide to the city of Atlanta. Calculating available rooftop coverage within the city gains an understanding of total potential vegetated roof coverage.

Quantification of different benefits of vegetated roof coverage can then be found using this total, such as energy savings, air quality benefits, stormwater reductions, and reduced health costs. Specific data is examined with tools such as the Landsat Explorer App from ESRI's Change Matters website, which allows for different areas of the globe to be compared over time in order to understand different land-use patterns which have occurred (ESRI 2020). Using this application helps to determine Atlanta's past development patterns and areas most in need of vegetated roofs.

After looking at the possible benefits of vegetated roofs within the city, as well as reviewing the best areas for their development, this thesis transitions to the discussion and conclusion sections, where the argument is made for the inclusion of vegetated roofs on commercial developments.

The Role of Landscape in Ecosystem Services

The term ecosystem services is widely defined by many sources. One classifies the term as "the components of urban forests that are directly enjoyed, consumed, or used to produce specific, measurable human benefits" (Escobedo, Kroeger, and Wagner 2011). The National Wildlife Federation defines ecosystem services as "any positive benefit that wildlife or ecosystems provide to people". They also claim the benefits can be direct or indirect, any size, and fall into one of four main services: provisioning, regulating, cultural, and supporting (National Wildlife Federation n.d.).

Provisioning services refer to more tangible benefits of nature which humans can extract. Things like food, water, wood, fuel, or natural gas fall under this category. Regulating services are all things which an ecosystem does to moderate the natural phenomena, such as erosion control, pollination, carbon storage, or regulating the climate. Cultural services are less material and defined by the role with which specific ecosystems play in the history or development of different cultures. This could be through recreation, or the ways in which humans gain knowledge through interactions with the landscape. Supporting services allow for the other three services to happen. Without this final service, ecosystems would not be able to thrive. Examples of supporting services are photosynthesis, creation of soils, the water cycle, and nutrient balance which are vital for the survival of ecosystems. (National Wildlife Federation n.d.)

Ecosystems are exceptionally important to the well-being of the human population. If not careful, air and water pollution, along with other environmental risks which come through human interactions with nature, can damage ecosystem services which are provided to cities and communities throughout the world (U.S. Environmental Protection Agency 2020b).

While all services could be discussed in relation to this thesis, the main services which will be examined will fall under the provision and regulating headings. Examination on the benefits of urban trees looks at their ability to provide cleaner air, reduce water pollution, and help cool local microclimates. Through implementation of vegetated roofs, the research question will look at the specific benefits to Atlanta in terms of air pollution uptake, stormwater reduction, and carbon sequestration. The specific human benefits of vegetated roofs will come through thermal comfort, noise reduction, cleaner air, potential food production, or aesthetically through the addition of greenspace on areas otherwise void of the luxury.

Ecosystem services provided by landscapes provide many aspects and luxuries of daily life often overlooked by the general public. Low pollution rates and properly functioning storm systems are much too often credited to human invention and innovation, rather than the role of landscape. Instead, proper education and recognition of the many natural processes happening just outside the window should occur. That is what this thesis will help to highlight. Trees, shrubs, grasses, and other vegetation are not just for aesthetics. They are able to benefit cities and human life in ways which should make them utilized as much as possible in urban areas.

Defining the Research Limits

This thesis examines the benefits of vegetated roofs within the city of Atlanta, GA in the United States. Founded as a railroad town in 1837, Atlanta has seen a lot of change in its relatively brief history. Atlanta, not originally founded as capital, was not laid out with grand ambitions or designed by a famous planner. Even so, the city has grown to become a major city on the global stage. Founded as the end of a railroad route that extended north to Chattanooga, Atlanta has become the global city it is today from its prominence as a transportation town during the Civil War. Since then, it has developed into one of the nation's top ten metropolitan economies (Allen 2014). Nearly destroyed during the Civil War, the city has rebuilt to be one of the most important financial, commercial and transportation centers within the United States. Atlanta is just over 134 square miles in size, is home to the busiest airport in the world, and has a total population within the city limits of just under 500,000 (Figure 1).

Atlanta's large growth has not come without its environmental setbacks. During the latter half of the twentieth century, between 1973 and 1992, the cost of Atlanta's growth was 380,000 trees. This rise in urbanization created an average loss of 55 acres of trees per day during this nineteen-year period (Weiler and Scholz-Barth 2009). From 1992 until 2001, the average loss went up even further, with some 250,000 acres of trees being removed, which is an average of 76 acres per day or a further 12% loss of tree canopy (Etienne and Faga 2014). Even with the sizable loss of tree canopy, Atlanta remained one of the largest forested cities in the United States, with tree planting initiatives through organizations such as Trees Atlanta helping to provide the city with close to half of its land being covered in urban tree canopy by 2009 (Giarrusso and Smith 2014).

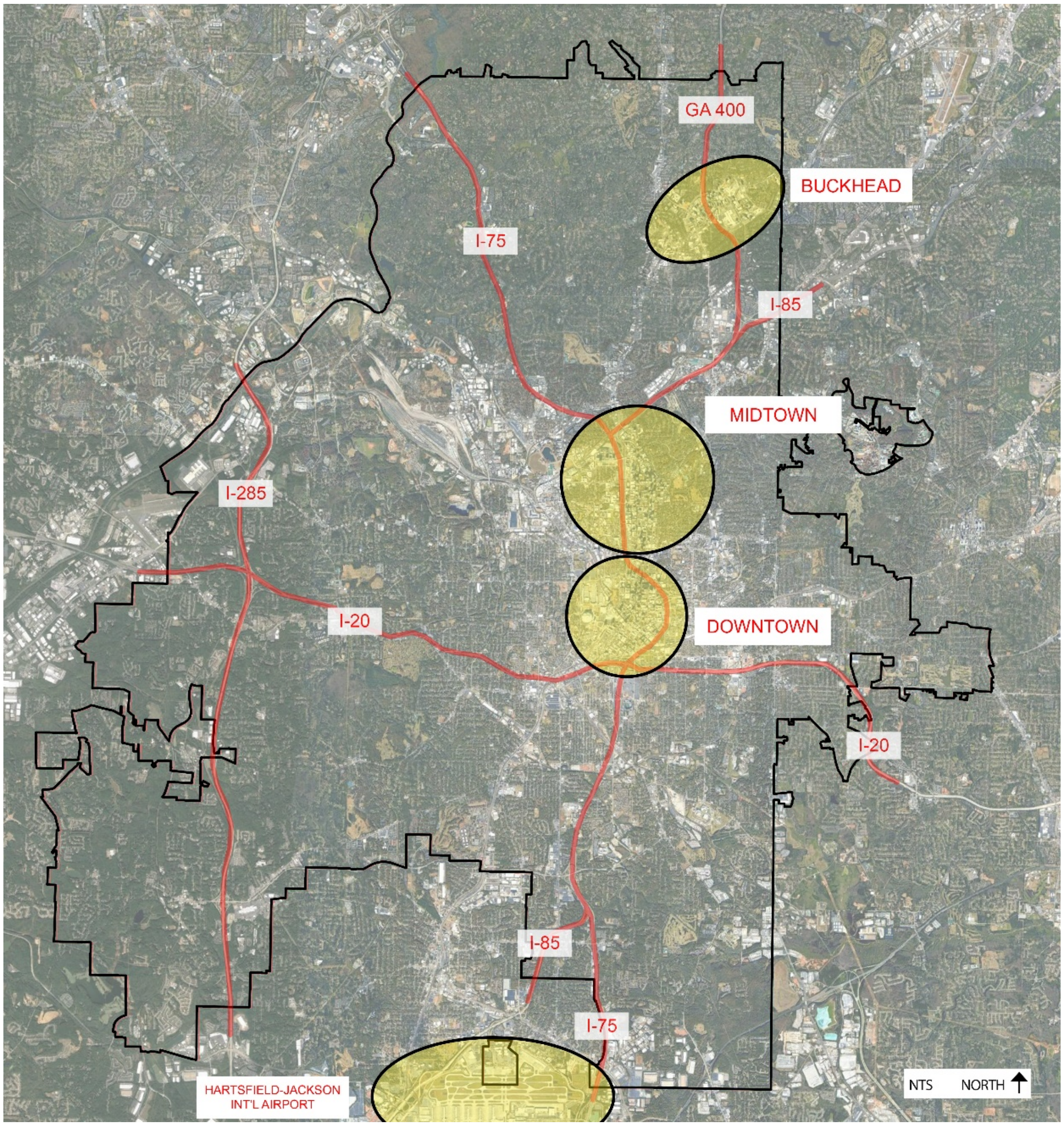

Figure 1: Context aerial of Atlanta, Georgia.
Source: (Google 2020b).

With Atlanta's global reputation, and as important as the tree canopy is to its identity, the city is surprisingly behind on the development of vegetated roofs within its limits. Other cities in the United States such as Portland, Chicago, Washington, D.C., and New York City are all well-known for their vegetated roof development and are far ahead of Atlanta in terms of total square footage of installed vegetated roofs. Even though Atlanta has a dense urban canopy, the population growth and urban expansion is slowly replacing the canopy with man-made surfaces and buildings. While the city requires recompense strategies, little thought has been given to what role buildings, and more importantly their roofs, can play in offsetting the canopy loss. By researching the benefits of vegetated roofs and the capabilities they can have in offsetting tree loss, it is the ultimate goal of this paper to elevate the environmental reputation of Atlanta globally so that the city is not just known as the city in the forest, but also the city under the sedums.

Delimitations

While some facts and figures throughout the thesis apply to the metropolitan region as a whole, all calculations to the benefits of vegetated roofs will take place only within the city limits. Any research into proposed vegetated roofs or calculations within the city will only focus on land not zoned single-family residential. Land designated by the city as medium-density residential, high-density residential, and very high-density residential is calculated, as these categories include townhomes, condominium buildings, apartment complexes, and multi-family buildings. While projective design helps to gain an understanding of the potential benefits which vegetated roofs have to the city, this thesis does not investigate the benefits or performance of specific plants, layers, or substrate materials of vegetated roofs. Schematic designs are shown in this thesis; however, they are included only to graphically illustrate the look of a vegetated roof. No planting plan, plant details, irrigation plan or schedule, or maintenance plan is discussed within this thesis. For total benefits to the city, different adoption rates of vegetated roof coverage are extrapolated off of a modeled 20,000 square foot (SF) extensive vegetated roof. These rates assume new construction or retrofits for buildings which are able to structurally support adding a vegetated roof. No structural tests are conducted on any buildings for this thesis.

Limitations

The calculations used for this thesis were developed by others and compiled through a review of the literature of journal articles, publications, websites, and previous studies on vegetated roofs. Due to project timeline and budget, there was not a possibility to do field research on a constructed vegetated roof test plot. Various computer models utilized in other studies were examined in order to determine their viability in assisting the overall research question, however they have not been used to answer the research question. Developers were contacted at iTree about using the iTree Eco software, previously known as the UFORE model, however they stated that while iTree Eco could help answer some of the benefit questions, the results would not be as accurate due to the software being programmed mainly for the benefit of trees to the environment, not vegetated roofs (i-Tree n.d.). If iTree were used, it would not be able to calculate benefits due to any difference in plant material. I-Tree Eco also requires conduction of field research through surveys of many plots throughout the study area. This would not have been possible due to the amount required for best results, as well as the ongoing coronavirus pandemic currently happening in the world. The ENVI-met software was also examined, however due to budget issues it was not able to be utilized (ENVI-met 2020). Future research, if able, could use ENVI-met as it appeared to be the best option for modeling widespread vegetated roof coverage in an urban area. When analyzing images gathered through ESRI's Change Matters website (ESRI 2020), GIS was not able to be used due to lack of knowledge on the software. Instead, a java-based computer program called ImageJ was used to help identify coverage of vegetation and urban areas in the city of Atlanta (ImageJ n.d.).

In the projective design section of the thesis, calculations show the benefits of a sample roof in terms of energy reductions, air pollution removal, and stormwater retention. The results are then extrapolated out over different adoption rates of the city based on available building square footage throughout the city of Atlanta. This square footage is found by taking the total square footage of buildings and removing the percentage of land zoned for single-family. Detailed information of roof type, slope, structural capacity, construction accessibility, and condition was not able to be obtained for every building in the city. Due to this, the calculations are based off of a best-case scenario of coverage, assuming that every rooftop in the total calculation is available for retrofit.

Due to the coronavirus pandemic, field research was not able to take place. Any specific data mentioned about any existing vegetated roof is compiled through a review of the literature. Attempts made to contact multiple sites in Atlanta in order to visit existing vegetated roofs were not responded to from management or any other employees.

Vegetated Roof Definition

Vegetated roofs are split into two main categories: intensive and extensive. Intensive vegetated roofs consist of a deeper substrate (typically > 6 inches) and more in-depth plantings, such as trees and shrubs. On some intensive roofs, it is even possible to have pools or water features incorporated into the design, and plants are sometimes maintained on an individual basis as they would be at ground level (Dunnett and Kingsbury 2008). In contrast, extensive vegetated roofs have a shallower substrate (usually 2-4 inches) and are more suitable for grasses, groundcovers or sedums. Extensive systems are sometimes regarded as more sustainable, as they may not require as much maintenance or resources as intensive vegetated roofs (Dunnett and Kingsbury 2008). One of these resources is irrigation. While most every plant needs water for initial establishment, many extensive roofs require only temporary irrigation, opposed to some intensive systems where irrigation is permanently installed for the success of the plant material. The temporary irrigation needed for extensive systems does not require permanent installed on the roof, helping to save on costs in the long run. Extensive rooftops may consider installing hose bibs which could allow for supplemental irrigation on the rooftop in times on extended droughts which can be common in the Southeast.

Extensive roofs are typically installed mainly for functionality, whereas intensive roofs are also functional, yet can be accessed and experienced on a regular basis. While both can be implemented on new construction, retrofits are typically extensive vegetated roofs. This is due to the fact that structural systems for existing buildings may not be able to support the added weight of intensive systems since they have deeper substrates and heavier plant materials.

Vegetated roofs are either permanently installed on rooftops or can be modular systems, where landscape inhabits individual trays placed on the roofs. This method of modular installation is mainly found in extensive systems, as the substrate depth in the trays does not support intensive systems. Vegetated roofs consist of five different layers; vegetation, soil, filter fabric, drainage and waterproofing, all on a structural deck (Hashemi, Mahmud, and Ashraf 2015). There is one additional classification of vegetated roof known as semi-intensive, which has a typical substrate of 6-12 inches and can accommodate grasses and small shrubs, however this paper will focus only on extensive and intensive vegetated roofs.

CHAPTER 2

LITERATURE REVIEW

Urban Development Patterns – Past and Present

The planet has recently passed a milestone never before achieved in its history: in 2008, more people resided in cities than in rural parts of the world. According to research estimates, this figure will reach 70% by the year 2050 (Birch and Wachter 2011). Unless something far beyond imagination happens in the future, this number is likely to remain above that mark. This projection illustrates how quickly the population has grown and urbanized in the past century, as well as allowing to better forecast what future population models will look like.

Due to urbanization, the world is at a higher risk of environmental hazards. These hazards include increased temperatures within city centers (urban heat island effect (UHI)), increased water runoff and reduced infiltration capacity of soils due to excess impervious materials, increased air pollution and greenhouse gases, and increased noise pollution. It is estimated that, on average, a city of one million people consumes just over 165 million gallons (506 acre-feet) of water, generates 132 million gallons (405 acre-feet) of wastewater, and produces 950 tons of air pollutants per day (Haughton and Hunter 2003). In the city of Atlanta, with a population of just under 500,000, water use has declined from over 100 million gallons (306 acre-feet) per day in 2000 to just over 62 million gallons (192 acre-feet) per day in 2009 (Atlanta Regional Commission 2014). Water use is predicted to further decline by up to 25% by the year 2050 (Chapman 2016). As global population rises and more people fill cities, these environmental problems will continue to grow, unless action is taken to build smarter cities.

Urban Heat Island Effect

The UHI effect is classified by the temperatures within cities being higher than their rural counterparts (Lee, Kim, and Lee 2014). The effect is especially apparent at night, as it takes longer for man-made surfaces to cool from the heat of the day than it does the natural landscapes outside of cities. Another contributing factor to the UHI is through stormwater. Due to more limited vegetation in urban areas, evapotranspiration of water back to the atmosphere is lower. Also, due to the increased impervious areas of urban centers, water cannot be recycled and flows more rapidly into sewers. These issues are both strong contributors to the UHI (Kendle and Forbes 1997).

Studies have shown that over the last half century, urban air temperatures have increased by an average of two degrees Fahrenheit (°F) per decade (Moran, Hunt, and Smith 2005), and could be as much as 12°F warmer than their surrounding rural areas (Sieghardt et al. 2005). As urban areas continue to grow and the climate of these areas increases, the number of heat wave days will also rise. The number of annual heat wave events averaged 14 days between 1900 and 1997, and could go up to as many as 50 in the near future. While this may not seem like a large number, a 1995 heat wave in Chicago lasted for only five days but killed around 500 people (Kahn 2006). A recent study on the effects of climate change on different urban areas found that as temperatures rise, not all urban areas will respond alike (Scheuer, Haase, and Volk 2017). Urban areas in North America, South America, Northern Europe, and Western Europe can expect increased temperatures to bring wetter conditions, increasing the risk of flooding. In contrast, urban areas within Central America, North Africa, and Eastern Europe differ and can expect warmer and drier conditions, causing longer droughts (Scheuer, Haase, and Volk 2017). Not only do surfaces such as asphalt and concrete contribute to the localized temperature increase, but so does every building with a bare rooftop. Due to the increase in air temperatures, energy consumption and generation within buildings rise, which leads to increased emissions and pollution within urban areas. This, in turn, creates smog and compromises the air quality of cities (Moran, Hunt, and Smith 2005).

Air Quality Impacts

Urban areas are also a major source for air pollution, as they are centers of industrial activity, energy production, vehicular use, and emissions (Haughton and Hunter 2003). Urban areas expose residents to around 200 different air pollutants. These air pollutants can cause health issues such as cardiovascular disease, asthma attacks, lung issues, and bronchitis (Sicard et al. 2011). The most harmful pollutants within urban areas are nitrogen oxides (NO_x), ozone (O_3), carbon dioxide (CO_2), sulfur dioxide (SO_2), and particulates. From 1960 to 2000, CO_2 alone increased within the United States at an average of 2.1% per year (KAHN). In 2015, Atlanta saw 8.5 million metric tons (MMT) of CO_2 emitted, which accounted for 0.13% of the total greenhouse gas (GHG) emissions in the United States (Distler 2019). As cities grow and more people live further from the economic centers, more mileage is driven commuting to and from work, as well as for every other daily task. As traffic increases and commuter distance travelled grows, emissions of more NO_x and carbon monoxide (CO) rise (Moran, Hunt, and Smith 2005). The World Health Organization (WHO) has studied air pollution within global cities and has released some staggering statistics. Estimates show that over 90% of the world's population under the age of 15 breathe in harmful air every day and in 2016 alone, over 4 million premature deaths were caused by ambient air pollution, of which close to 300,000 were under the age of five (World Health Organization 2018). Studies show air pollution damages within the United States alone costs the country roughly 5% of its gross domestic product per year (Robinson 2019). The good news is that this trend has been declining in the past 20 years and, while this may not seem a major percentage, when looked at from a dollar amount it is staggering. For example, in 2014, the damages due to air pollution cost the United States around $790 billion United States dollars (USD) (Robinson 2019).

Water Impacts

Another negative environmental impact of urbanization is increased water runoff and reduced infiltration capacity of soils. With the increased urban footprint, cities remove naturalized areas such as forests, meadows, and grasslands and replace them with man-made infrastructure such as concrete, asphalt, buildings, and other impervious surfaces. Soils get heavily compacted during construction, and even some areas not built, or which remain lawn, have a hard time achieving the same level of permeability that they may have had pre-construction. Due to this, along with the temperature rise, need for irrigation, and wetter conditions in some urban areas, storm system limits are being exceeded and flooding is increasing (Moran, Hunt, and Smith 2005). While cities contain with complex infrastructure designed to collect and transmit stormwater, increasing imperviousness in urban areas is testing these limits. For the city of Atlanta, one inch of rain equates to almost 2.3 billion gallons (7,058 acre-feet) of water within the city limits (U.S. Geological Survey n.d.). In 2018, Atlanta saw one of its highest years of rain with 70 inches recorded, or 161 billion gallons (4,940,880 are feet) of rainfall. Urbanization not only requires careful planning, but it also requires developers to think about the impact of stormwater management at the project, city, and global scale (Moran, Hunt, and Smith 2005).

Tree Canopy Impacts

Along with these environmental hazards, the tree canopy is also at risk due to urbanization. Trees have many benefits to urban areas, such as neutralizing pollutants and eliminating particulates in the air (Sieghardt et al. 2005). Through added development, cities are losing more of their natural landscape. Although cities replant trees as part of recompense, they can rarely provide the same benefits of the pre-developed landscape immediately. On a positive note, the continued development of cities is providing more rooftops every year, allowing for the possibility to help offset the loss of the urban tree canopy with the implementation of vegetated roofs. By better understanding the state of the world's urban population numbers and future models, there is an ability to design better, smarter cities with more vegetation in order to help combat these environmental issues.

Population Growth

If you were to look at a graph of the world's population, especially for the population that resides in cities, it would remain relatively flat for the majority of human history. It was not until around the year 1800 when the city populations started to increase to where they are today. The world saw its population reach one billion people in 1804, two billion in 1930, three billion in 1960, four billion in 1974, five billion in 1987, six billion in 1999, seven billion in 2011, and current predictions show that the world will hit eight, nine, and 10 billion in the years 2023, 2037, and 2057 respectively ("World Population Clock" 2020). Looking at those figures shows that it took millions of years for the global population to hit three billion, while it will only take 34 years to add another three billion between 1987 and 2023.

Beijing, China was the first city to reach the population milestone of one million people, which occurred in the early 1800s (Gordon 1990). At that time, the world's population was at one billion people with just five percent of people living in urban areas (Haughton and Hunter 2003). In 1950, when the population of the world was at two and a half billion, urban area population had grown to 17% (Bazoglu 2011). By 2000, with a world population of just over six billion, over 46% of the population lived in urban areas. Today, with a world population of over 7.75 billion people, over 4 billion people are living in urban areas, or just over 56% of the total population ("World Population Clock" 2020). This number is only expected to rise, with close to

6.7 billion urban residents predicted by the year 2050 (United Nations 2019).

Since the first city with one million residents in 1800, many more cities have passed that milestone with the expanding global population. In 1900, 16 cities in the world had a population of more than one million people. That number grew at an astounding rate through the mid-1900s; by 1980, 235 cities across the globe had more than one million residents (Gordon 1990) with the largest amount of growth happening in the 1970s. Within the United States, over 35% of the population in 1960 lived in a city of more than two million. In just 40 years, by 2000, 50% of the population resided in cities of more than two million people (Kahn 2006).

In 1990, the world had 10 megacities, cities with a population of 10 million or more. In 2018, there were 33 megacities, with six of those alone in China. Forecasts show there could be 43 megacities by 2030. In 1970, there were 55 million total people living in megacities around the world, which accounted for 1.5% of the population. In 2030, that number is expected to be 752 million people, or 8.8% of the population. (United Nations 2019)

Looking at global population numbers is eye-opening. From the start of human history until 1930, nobody who had ever lived had seen a doubling of the population in their lifetime. Estimates predict that anyone born after 2050 will also not see a doubling of the population (Cohen 2011). With the global population at two billion in 1930 and four billion in 1974, a doubling of the global population occurred in 44 years. It took the world from the beginning of time until 1804 to reach one billion people, whereas it only took 12 years, from 1999 to 2011, for the population to grow from six billion to seven billion people.

Atlanta has seen a drastic amount of change and urban growth in its short history. Founded in 1837, Atlanta was so small and insignificant that it was hard to believe the city would grow to be what it is today within the world’s stage. The city’s earliest essential function was to serve as an outpost at the end of a railroad line up to Chattanooga. The railroad brought both economic growth and population growth to the city, with roughly $200,000 USD of annual trade in 1849 to over one million USD in 1851 (Ambrose 2003). From 1837 until 1860, the city experienced moderate growth and had close to 8,000 residents by the time the Civil War started. During the war, and because of the city's prime location within the Southeast, the population started to rise. By the end of the war, the city had a population of more than 22,000, making it the third-largest city in the South, and was the self-proclaimed "Gate City of the South" (Ambrose 2003).

In the late 1800s, following the near destruction of the city during the Civil War, growth and rebuilding happened quickly. In 1866, the economy of Atlanta started to rebound and was doing an estimated $4.5 million USD in business (Ambrose 2003). The city population doubled between 1860 and 1870, and cotton textile mills were helping the city thrive. The 1880s saw cotton production nearly triple and by 1890, the commerce of Atlanta was valued at almost $115 million USD (Ambrose 2003).

At the turn of the twentieth century, Atlanta had grown to a population of close to 90,000, and further tripled in size by 1930. At that time, the city was the 29th largest city in the United States (Ambrose 2003). From 1940 until 2000, the population of the city only grew slightly more than 100,000, but the metro population exploded to over four million residents. Much of this metro growth was during the 1990s and by 2000, Atlanta was the fastest growing metro population in the nation, then home to about 300,000 residents.

Commercial construction within the city took off in the 1960s, when the city saw 17 skyscrapers of at least fifteen floors go up (Ambrose 2003). Following the construction of Lenox Square in 1959, Atlanta saw the addition of multiple shopping centers as well as office parks, and over five million SF of office space was constructed between 1965 and 1971 (Ambrose

2003). Today, Atlanta is home to over 100 skyscrapers, 320 high-rise buildings, and has 63 buildings over 400 feet in height (Emporis 2020).

Even though Atlanta is recognized as a commercial and cultural center of the United States, the city is surprisingly not very large, being only 134 square miles in size. Even so, the metro area is one of the top ten in the nation, with land totaling up to 6,100 square miles (Heath and Heath 2014) and a population of over six million. The city's total population of just under 500,000 represents slightly more than 8% of the total metro population, making it one of the lowest city-to-metro population ratios in the United States (Heath and Heath 2014).

With all the growth that Atlanta has experienced over the past 60 years, mass suburban sprawl and traffic congestion have contributed to many environmental issues, such as air pollution. Due to the increase in the urban and metro areas, Atlanta has also seen a large loss of trees and greenspace, which have contributed to local water pollution (Ambrose 2003). During the 1990s, the Atlanta metro region grew by about 200 square miles, or around 125,000 acres. This equates to around 4,000 SF of constructed asphalt, concrete, and building surface per person, on land that was previously forested, during that time (Vargo 2014).

During the 2000s, urbanization continued within the city limits. Below are three graphics of urban areas within the city of Atlanta, all gathered with the Landsat Explorer App through ESRI Change Matters (ESRI 2020). Urban areas from September 2000 (Figure 2) are overlaid with the same statistic from September 2019 (Figure 3) to illustrate the growth which has taken place within the city in just 19 years. While the different colors in Figure 3 may not seem like a lot, when isolated and shown in red (Figure 4), it is possible to see just how much land urbanization claimed in that short time frame. Using a figure-ground style of calculation, the computer program ImageJ is able to read the amount of coverage in each image (ImageJ n.d.). Using this

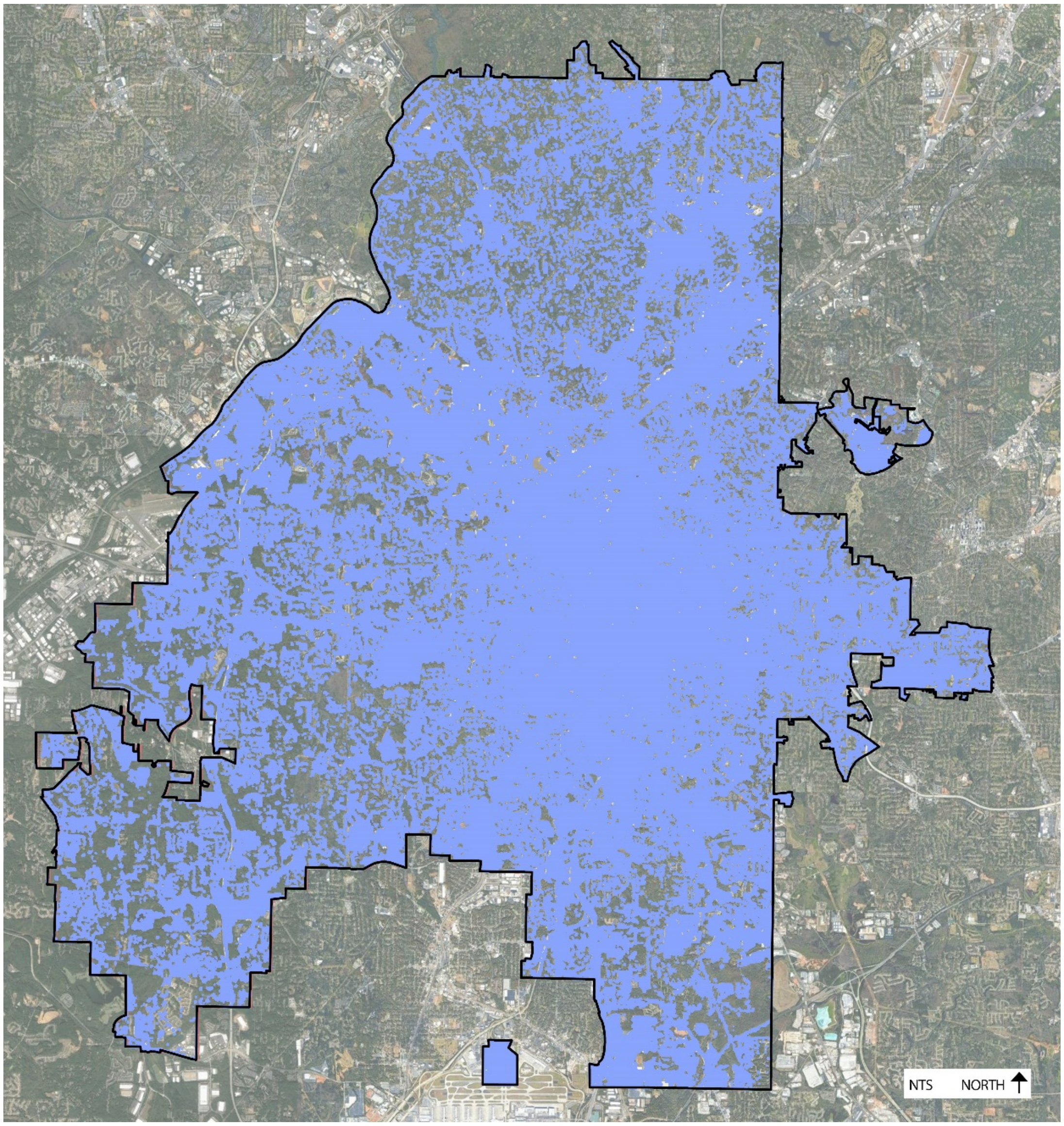

Figure 2: Urban areas within the city of Atlanta in 2000.
Sources: (ESRI 2020); (Google 2020b).

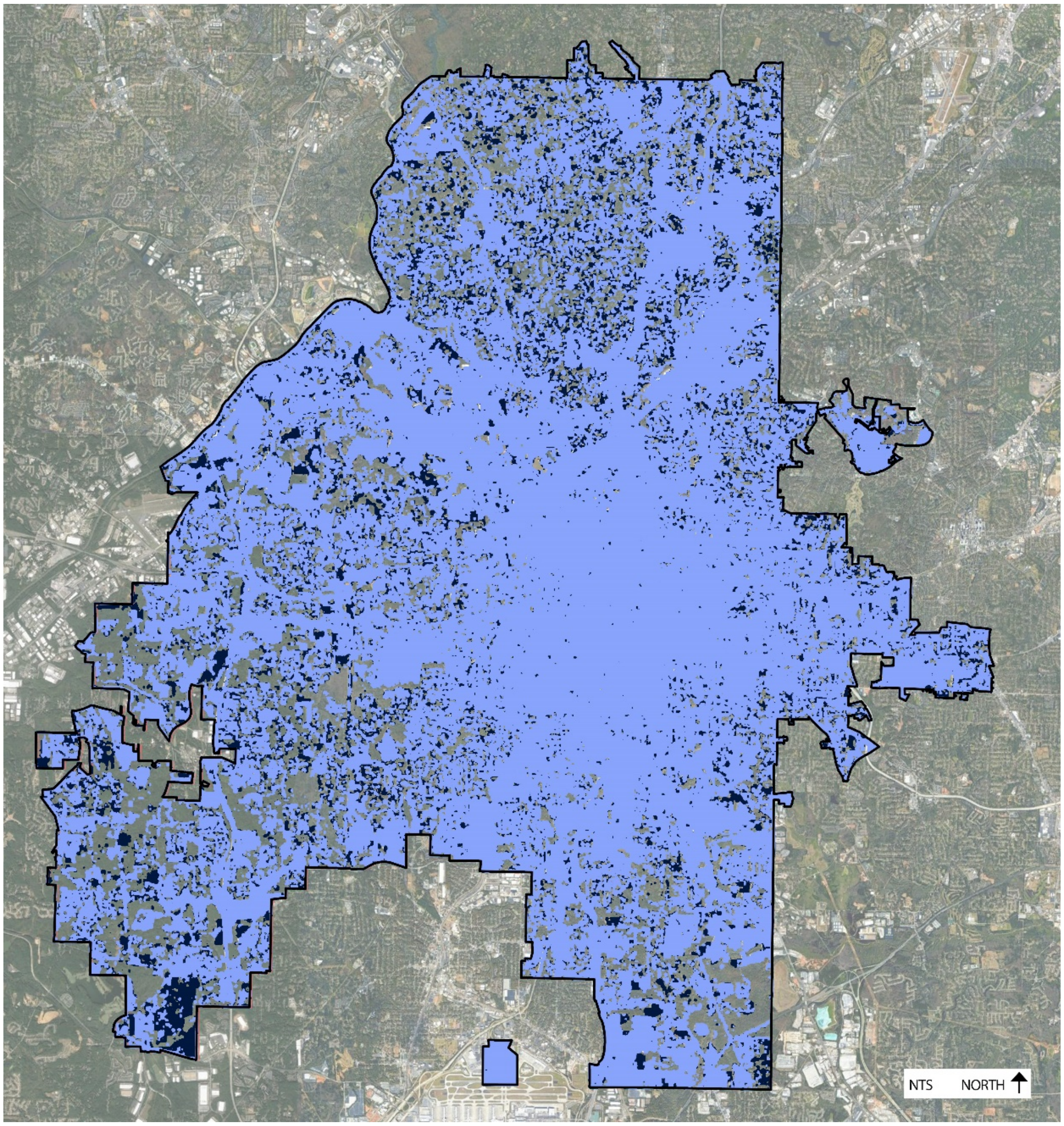

Figure 3: Urban areas within the city of Atlanta in 2019. Urban areas from 2000 are shown in light blue, while 2019 is shown in dark blue below to illustrate growth.
Sources: (ESRI 2020); (Google 2020b).

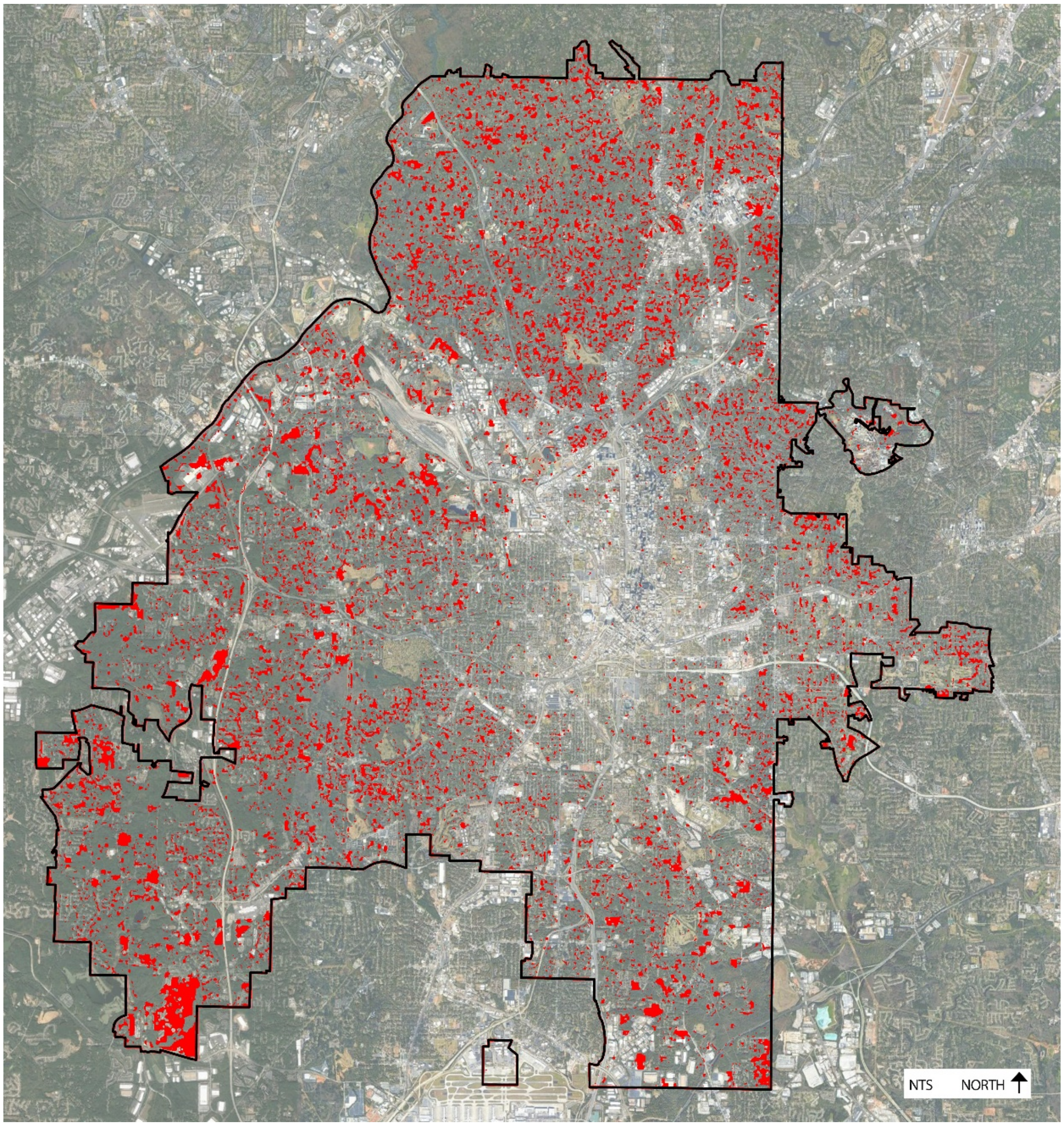

Figure 4: Urban area growth in Atlanta between 2000-2019.
Sources: (ESRI 2020); (Google 2020b).

program, it is possible to read each image and find that a 5.83% increase in urban coverage has taken place from 2000-2019. By 2040, estimates say there could be up to 1.2 million people living inside the city limits of Atlanta, almost triple what there is today (Carnes 2019), with metro growth reaching more than eight million people. This would put the city fourth in the nation of metro population, slightly behind Chicago.

By 2025, close to 1,250 cities worldwide will have a population of over 500,000 people (Birch and Wachter 2011), which equates to roughly 1,250 Atlantas in the world. By that time, and continuing into the future, city developers need to ask essential environmental questions which face growing populations, especially within urban areas. Within the United States, projections show that by 2050, urban areas may grow to 8.1% of total land area, which is greater than the size of Montana (Nowak 2006). If the United States continues to grow as predicted, focus on design and implementation of cities needs to ensure they are environmentally sustainable for both the current generation and the generations to follow. One main principle for a sustainable approach to urban development is that prevention is better than the cure (Haughton and Hunter 2003). Therefore, it is important to approach development with caution, ensuring that all impacts of development are properly studied, including economic, environmental and social impacts. One potential way of creating smarter urban development is through early public participation and education on issues such as green infrastructure and sustainability. This can help enhance stewardship of the land within the community and in turn positively affect the environment. The saying ‘think globally, act locally’ applies here, as it challenges residents, developers, and policymakers to not just improve the environment around their city, but to think of the planetary consequences of their actions (Haughton and Hunter 2003).

Climate Impacts from Urbanization

This section focuses on environmental setbacks and implications caused due to rapid population and urban growth. While growing cities and urbanizing economies have many positive impacts socially, economically, and environmentally, there are also some negative aspects, which, if left unchecked, can harm humans, plants, animals, and the environment as a whole. Due to the rapid population growth and rise in urbanization within the past two to three centuries, there are several environmental setbacks, including the rise of the UHI, air pollution, and water pollution.

Up until a few hundred years ago, the lack of transportation and circulation available limited urban growth. People would tend to stay in the areas they were from unless they wanted to undertake a costly, and sometimes dangerous, trip via horse and wagon to a new town. Upon the completion of many of the railroads, urban development started to grow. In the early 1900s, production of the first cars allowed humans the ability to move about easier and contribute to urban growth. Less than 15 years after the advent of assembly line production, there was one car for every six people in the United States. By 1950, that number had increased to one car for every 2.8 people (Miess 1979). In 2019, there were just under 285 million registered cars in the United States. When this is compared to the population, the United States now sees one car for every 1.15 people (Hedges & Company 2020). This statistic helps to showcase how much the world is changing, how quickly and easily urbanization is happening, and how the rise of the car and urban areas are contributing to global climate change.

Since almost the beginning of time, humans have contaminated the environment with air with smoke pollution. The smoke pollution effects were very minimal until about the thirteenth century, when it was discovered that coal fires were producing winter fog in some cities (Mellanby 1967). In the nineteenth century, industrial development boomed and started to pollute the environment on a scale never before seen. In the mid-1900s industrial development caused over 1,000 tons of grit and dust fell over every square mile of industrialized areas per year. This number equates to about two pounds of grit and dust on every square yard (Mellanby 1967). Due to the industrialization of the 1800s and 1900s, lung cancer was higher in cities than rural areas, as were respiratory diseases and other health issues. While much of the world has now realized the health issues of urbanization and has begun to reduce some of the negative aspects which go along with it, there is still a long way to go to make cities healthy for all citizens.

Design of cities can go a long way to determine their overall health, as well as their regional output of pollution. Designs work hand-in-hand with the regional climate to determine the amount of atmospheric pollution given off. When planning and constructing, more harm than good can be caused to the overall urban fabric of towns if not planned properly. Eight of the past 10 years have fallen in the top 10 hottest years on record globally, with the past five years all being the hottest on record (Climate Central 2020). Even though climate change and changes in biodiversity have been taking place throughout history, the speed of change has increased to an extent not previously seen (Hagen and Stiles 2010). In order to properly thrive and function, cities need healthy ecosystems and biological diversity. One of the dangers of climate change is the alteration of plant compositions and trends within cities. Through design of cities, consideration needs to be taken of plan species that can help mitigate the effects of current and future changes within the climate. Due to the changing climate, adverse effects will include; warmer weather, causing fewer cold days and nights, more hot days and nights, more heatwaves, larger areas of droughts, and heavier precipitation events (Nowak 2010).

As previously mentioned, urban areas are contributing to the rise of UHI, air pollution, and water runoff issues. The first issue with urbanization, and one of the most serious, is the

UHI effect. This is caused by increased temperatures within city centers compared to adjacent rural areas and can vary in intensity based on the location and size of the urban area. As urban areas are comprised of up to 60-70% of man-made surfaces such as concrete, asphalt, and buildings, they soak in more radiation. Central areas of large cities can be warmer than rural areas between four and six degrees Celsius (°C), and on occasion even up 10°C warmer (Miess 1979). In May 1997, temperature data collected using thermal sensors on aircraft in the urban core of Atlanta found that the average air temperature was around 80°F. The aircraft flew over different surfaces and the resulting data showed that for man-man areas, the temperatures were over 100°F and building roofs held the highest temperatures at almost 120°F (Estes, Quattrochi, and Stasiak 2011).

Aside from built surfaces storing heat, they also contribute to the UHI through their reflectivity. This reflection characteristic is known as albedo. Built surfaces such as concrete, asphalt, and roofs have low reflectivity quotients compared to that of natural areas like trees, grasses, and other vegetation (Estes, Quattrochi, and Stasiak 2011). Because vegetation absorbs sunlight and uses that energy in evapotranspiration, it helps to cool the surrounding air instead of storing heat like that of man-made surfaces. While vegetated roofs aid in lowering the UHI, other options for bare rooftops are available, such as white roofs. White roofs are simply roofs with a light colored surface which helps to reflect light back into the atmosphere and thus can help to keep building interiors cool (Opatowski 2018). Installation of white roofs comes at a cheaper price than vegetated roofs and they can have direct impacts to the building and adjacent temperatures. However, these roofs still contribute to stormwater runoff, are not able to capture air pollutants, and do not last as long as vegetated roofs last.

The effects of UHI are often most noticeable on calm, clear evenings following sunny days. This is due to the fact that rural areas tend to cool faster than cities do, especially at night, allowing for the temperature difference to be felt. Higher temperatures often result in increased energy demand during the summers, contribute to global warming, and increase the amount of air pollution within cities. Also due to the UHI, rainfall increases in areas downwind of city areas. A 2017 study into this effect in the Atlanta area showed that daily precipitation was highest to the northeast of Atlanta, followed by the urban core of the city, the east of the city, and the north of the city. These findings were consistent with the climatological downwind areas of the city based on wind rose analysis (McLeod, Shepherd, and Konrad 2017) .

The UHI contributes not only to higher air temperatures, but also higher air pollution. Due to the UHI, the warmer air in urban areas rises and draws in air from surrounding rural areas. This combination forms a circulation system which creates a dust dome and can hang over cities, which in turn traps pollutants (Haughton and Hunter 2003). This helps in degrading the overall air quality in urban areas, which contributes to the formation of ozone, carbon emissions, and other harmful air pollution. Not only does this pollution have an effect on human health, but it also has a sizable one to the economy. In 2014, air pollution cost the United States $790 billion USD, or 5% of its GDP (Robinson 2019).

Ozone is mainly formed through intense sunlight, warmer temperatures, and the interaction of volatile organic compounds (VOCs) and NO_x (Estes, Quattrochi, and Stasiak 2011). When temperatures rise above 90°F, ozone is more affected and can become more dangerous than normal. Effects to human health from ozone can include inflammation of lung tissue, asthma, and other respiratory issues. In a 1989 study, it was calculated that a reduction of just .01 parts per million (ppm) in ozone within the United States would minimize chronic respiratory disease by one million cases, saving around one billion dollars USD per year (Haughton and Hunter 2003). In the latest 'State of the Air' report from the American Lung Association, Fulton county, where the majority of Atlanta is located, received an "F" ozone grade. While the average number of high ozone days has decreased from 95.5 in 1998-2000 to 7.5 in 2016-2018, Atlanta is still above the number of days needed to achieve a passing grade, which is 3.2 (American Lung Association 2020a). Aside from ozone, other major classes of air pollution within urban areas include carbon oxides, NOx, particulates, sulfur compounds, SMOG, and VOCs.

Through the burning of fossil fuels, CO_2 is a heavy contributor to the greenhouse effect, which is causing the planet's average temperature to continually rise. Currently, transportation is the highest contributor to greenhouse gas emissions, with electricity and industry right behind (U.S. Environmental Protection Agency 2020c). Before 1900, the highest previous concentration of CO_2 was roughly 320,000 years ago, when it hit 300 ppm. In 1958, global CO_2 was at 315 ppm and in 2015, it surpassed 400 ppm for the first time in history (Lindsey 2020).

While CO_2 is a naturally occurring gas required for plant and animal life, carbon monoxide (CO) is not naturally occurring but is just as dangerous. CO releases into the atmosphere through burning. Its largest contributors are, like CO_2, also transportation and industry. CO is harmful to humans, as it slows the amount of oxygen available for transportation to the blood stream and critical organs. This can lead to a number of health issues such as cardio-vascular disease symptoms and headaches (Haughton and Hunter 2003). Over the past 40 years, the United States has seen an 85% decrease in CO concentrations (U.S. Environmental Protection Agency 2020a).

The two most common forms of nitrogen oxides (NO_x), and the most hazardous to the environment, are nitric oxide (NO) and nitrogen dioxide (NO_2). These can be especially hazardous when combined with sulfur dioxides as they form to create acid rain, ozone, and increased particulate matter. While the majority of worldwide NOx is through natural causes such as decomposing organic matter, fires, and lightning (Haughton and Hunter 2003), humans produce the majority of NO_2 through the burning of fuel in cars and other forms of transportation, as well as through power plants (U.S. Environmental Protection Agency 2016). It is hazardous to human health through increased respiratory issues such as asthma in the elderly and children. Even though this form of air pollution can be a health hazard, the United States has seen a 36% decrease in the national average of NO_2 since the year 2000 (U.S. Environmental Protection Agency 2016). From a local standpoint, Atlanta has stayed far below the national average of NO_2, which is 53 parts per billion (ppb) and in 2014 the city measured in at only 10 ppb. Atlanta has also seen a 42% decrease of NO_2 from measuring years 2005-2007 to 2009-2011 (Georgia Department of Natural Resources 2015), and the state of Georgia has reduced emissions by 60% since 1990 (Environmental Protection Division n.d.).

Particulate matter (PM) is an overarching term which constitutes the mixture of solid particles with liquid droplets (U.S. Environmental Protection Agency 2018b). Some forms, such as dust, dirt, smoke, soot, and pesticides are large enough to be seen by the naked eye and fall into the PM_{10} category, which designates particulates with a diameter between 2.5 and 10 micrometers. This type of PM is able to enter human airways and can affect the upper respiratory system (Sœbø et al. 2017). They can also remain in the atmosphere for many days and one of the main sources of this pollutant is power generation. Although particulates can be greater than 100 micrometers in diameter, those tend to be removed from the atmosphere and are not as big of an issue (Haughton and Hunter 2003). The other main designation of particulates is $PM_{2.5}$, which are particulates with a diameter of less than 2.5 micrometers. These tend to be the greatest health hazards, as they can get in the bloodstream and lungs, causing major health issues, and are generally the cause of haze within the United States (U.S. Environmental Protection Agency 2018b). Aside from human health concerns, particulates can block stomata on leaves, affect photosynthesis (Sœbø et al. 2017), and are the main cause for buildings, paint, statues, and vehicles looking soiled or dirty. They also have been found to reduce photosynthesis in plants, as much as one-tenth the normal rate in some areas of heavy contamination (Gill and Bonnett 1973). Particulate emissions have been decreasing in Georgia at a rate of 61% for $PM_{2.5}$ and 51% for PM_{10} since 1990 (Environmental Protection Division n.d.). Within Fulton County, particulate matter counts fell below the pass line for annual average concentration for the first time in 2013 and have continued to stay that way (American Lung Association 2020a). Even with these declining numbers, it was still estimated that in 2003, close to 40 million people in the United States lived in areas where the USA EPA standard for particulates was exceeded (Haughton and Hunter 2003).

Sulfur has the ability to enter the atmosphere in gas or liquid form, or as sulfate salts attached to particulate matter (Haughton and Hunter 2003). The gas comes in the form of sulfur dioxide (SO_2) and the liquid is in the form of sulfuric acids. Over the past 30 years, Georgia has seen a major reduction in SO_2, cutting emissions as much as 95% (Environmental Protection Division n.d.). The most common source of SO_2 is through power plants and industrial activities. There are health risks associated with SO_2 to both humans and the environment. For humans, it can cause respiratory issues, especially in children, and can attack the lungs. For the environment, SO_2 can decrease growth in plants, cause acid rain, and cause haze within cities which reduces visibility (U.S. Environmental Protection Agency 2019b). The United States seems to be on par with Georgia, having reduced SO_2 concentration by 92%, decreasing from over 250 ppb in 1980 to less than 50 ppb in 2019.

Smog, a term created in the 1900s, is a type of air pollution describing a mixture of smoke and fog which can seemingly hang over urban areas (Haughton and Hunter 2003). It can describe industrial or sulfurous mixtures, or secondary photochemical oxidants within the atmosphere. It is normal for both types of smog to be present over urban areas, although not necessarily occurring at the same time. Industrial smog is usually found during summer, while sulfurous smog is typically found during winter (Haughton and Hunter 2003). Atlanta's smog levels have fallen slightly in the past 10 years. Smog data from Georgia's Ambient Air Monitoring Program found that in 2010, Atlanta experienced 223 days at category yellow (moderate air quality), two days at category orange (unhealthy for sensitive groups), one day at category red (unhealthy), and the remaining days at category green (good). In 2015, those numbers were 165 days at yellow, one at orange, and the remainder at green. From the start of 2020 until writing, Atlanta has experienced only 11 days at yellow and one day at orange (Georgia Air Monitoring 2020).

Air pollution can also take the form of VOCs. These come from a variety of sources, both natural and anthropogenic, including paint and gas cans, as well as natural sources such as vegetation (Estes, Quattrochi, and Stasiak 2011). Plants are natural emitters of VOCs, so forests, grasslands, swamps and other natural areas have the ability to emit significant quantities of these chemicals (Haughton and Hunter 2003). Available data has shown that people in urban areas can be exposed to up to 1,000 times the concentration of VOCs compared to those in rural areas (Haughton and Hunter 2003). Studies have shown that the United States has reduced emissions of VOCs by almost 50% since 1990, while Georgia's reduction is almost at 54% (Environmental Protection Division n.d.).

Atlanta has improved its air quality over the past 30 years, however compared to other United States cities it is still in need of improvement. In the latest state of the air report, Atlanta ranked 33 out of 229 metropolitan areas for high ozone days and 23 out of 204 metropolitan areas for annual particle pollution (American Lung Association 2020a). In a separate report, it was found that Georgia ranked 40 out of 50 states in air pollution for 2019 (United Health Foundation 2019) .

While the overall trend for these air pollutants is that Atlanta, the state of Georgia, and the United States are decreasing their outputs, millions of people are still at risk from their adverse effects. According to the American Lung Association, their 2016-2018 report showed that over 137 million people lived within counties which earned an "F" grade for ozone (American Lung Association 2020c). This is attributed to the warmer temperatures that are being experienced each year, which helps ozone to form and makes it difficult to clean. Further, it was found that almost 46% of United States' residents are living in areas with unhealthy levels of either ozone or particulate pollution (American Lung Association 2020b). Some of the residents at risk due to air pollution include the younger and older populations, those with cardiovascular issues, those with lung issues, chronic obstructive pulmonary disease (COPD), and those with asthma. Putting an economic value on just one of these health risks, it was found that in 2007, the total cost of asthma to the United States was over $56 billion USD (Barnett and Nurmagambetov 2011).

As the population continues to rise and cities continue to grow, so too will the UHI. This is, unless smarter planning and design methods are implemented. As discussed, the UHI modifies urban climates, contributes to increased air pollution, and changes local meteorology. Studies indicate that if the temperature of a city can be cooled by just 5°F, large benefits are seen (Estes, Quattrochi, and Stasiak 2011). This temperature change would bring about less solar intensity which helps to create ozone and smog, would improve public health, conserve energy, and benefit urban environments. The one thing the world wants to make sure to avoid is inaction against climate change, as this could lead to continued decline in the urban environment and could see a rise in sprawl due to unwanted urban conditions.

As urban areas continue to grow, man-made impervious surfaces such as concrete, asphalt, and rooftops continue to dominate the landscape. A general rule for urban areas is that around a third of all surfaces are roads and paths. Another third is occupied by buildings, which means that on average, close to 65%-70% of urban areas are man-made (Miess 1979). Through this process of urbanization and these new surfaces being built on top of natural land, the ground surface is altered and no longer functions as a means of water percolation during rain events. Since water is now sheet flowed across surfaces, runoff accelerates and can overwhelm the storm systems. While some water that falls on concrete or asphalt has a chance to flow towards the landscape, pipes collect water that falls on rooftops and either transport it to a concentrated swale or directly into the storm system. Many of the airborne pollutants within cities which eventually settle on impervious surfaces are picked up by stormwater, taken into the sewer systems, and eventually make their way to streams and rivers (Moran, Hunt, and Smith 2005). When the amount of imperviousness increases within cities, more water runs across surfaces and picks up these pollutants, adding to the issues within the water sources. In Atlanta, almost 99% of the water supply comes from surface waters, such as Lake Lanier and many local rivers (Atlanta Regional Commission 2014).

In a 2014 presentation, the Atlanta Regional Commission showed that over the past 30 years, Atlanta was ranked fourth amongst the nation’s top metropolitan areas in total rainfall, averaging 50 inches per year (Atlanta Regional Commission 2014). One inch of rain equals roughly 2,293,000,000 gallons (7,036 acre-feet) of water for the city of Atlanta (U.S. Geological Survey n.d.). Multiplied by the average rainfall for the year, Atlanta has to manage around 114,650,000,000 gallons (351,848-acre-feet) of water annually. In 2018, the city had 70 inches of rain, one of the highest years on record. This extra 20 inches added an additional 45,860,000,000 gallons (140,739-acre-feet) of water that fell on the city. Atlanta’s per capita water use is around 110 gallons a day, or just over 40,000 gallons (0.12 acre-feet) a year (U.S. Geological Survey n.d.). If all the water that falls on Atlanta were collected and stored, it would be enough to meet the needs of over 2.5 million residents, more than five times what the total population is today.

Rainfall is important as it helps to provide water to the root zones of plants in natural areas, helps crops, and helps to feed plants in urban environments (Moran, Hunt, and Smith 2005). Urban areas inhibit the natural hydrologic cycle by preventing precipitation from seeping into the ground and working its natural system with the plants. Instead, it takes rainwater and directs it on the quickest route to the nearest storm drain, through sewers, and into a discharge area. It is estimated that some cities, due to stormwater runoff, lose enough water that could supply over 3.5 million people with average household water needs (Moran, Hunt, and Smith 2005).

Cities have started to see the issue that has arisen with stormwater management over the past few years and have started to pass stormwater ordinances. Atlanta, for example, passed one of the leading ordinances in 2013 called the Post-Development Stormwater Management Ordinance. Applying to nearly every type of construction, the ordinance states that, through green infrastructure, the first one inch of rainfall must be captured on-site before any stormwater goes into the sewer system. Since its passing, it is estimated that the city has kept over 1.1 billion gallons (3,375 acre-feet) of stormwater out of its sewers and creeks per year (City of Atlanta 2020b). While this is a great start, there is still more that can happen to eliminate excess runoff and water pollution within cities.

While the overall trend for the majority of environmental issues due to urbanization looks good over the past 30 years, especially within the United States, there is still room to make cities even healthier. The United States is passing stricter development policies, such as the EPA Clean Air Act, and local municipalities are adopting policies, like Atlanta's Post-Development Stormwater Management Ordinance, in order to improve regional environments.

Trees in Urban Design

Human history with tree cultivation dates back thousands of years. This does not mean, however, that oaks, elms, maples, or lindens have richly populated cities since that time. Trees were a luxury item in those times, with early tree use being for the wealthy; appearing in private gardens, palaces, and on the properties of wealthy land owners. Some of the earliest known uses of trees was recorded 10,000 years ago when nomadic civilizations started to cultivate fruit trees for food instead of having to depend solely on hunting and gathering (Hauer et al. 2017).

Records kept by the Egyptians denote trees used in temple gardens, along with main corridors of travel. This is perhaps the first "urban design" use of trees in human history. For the Egyptians, trees provided more than just food. They were used for fuel, wood, materials, medicine, and shade (Hauer et al. 2017). In the hot desert climate of Egypt, their trees were valued for the shade they provided, and the gardens of Egyptian rulers had rows of fig trees, palm trees, and pomegranate trees (Hauer et al. 2017). Aside from use for shade, medicine, fuel, and wood, some countries used trees for ship building while others placed them along roadsides in order to demarcate where the edge of the road was when it snowed in the winters.

Further examples of ancient tree plantings are found in records from the eastern Mediterranean region of Levant, which lies near the border of present-day Syria and Turkey. It was here, between 6,000 and 8,000 years ago that olive trees were first domesticated (Campana 1999). In China, records of trees began around 200 BC. In Greece, there are records which detail plantings in the Agora, the market nearby the Acropolis in Athens (Forrest and Konijnendijk 2005).

Medieval cities did include tree plantings in their designs, however most of these were in private gardens inaccessible to the public or on farms outside of the city center (Lawrence 2006). Some of the first public uses of trees in an urban sense began during the Renaissance when Italy started to develop villas in the 1500s. Trees were included along pathways, used for strolling about the villas, and groves of trees were planted for woods as part of the estates (Hauer et al. 2017). As villas became more popular, they spread to other countries, along with the use of trees for public use. In France, King Henry II issued an ordinance which called for the planting and maintenance of trees throughout Paris in 1552, which was the first of its kind (Forrest and Konijnendijk 2005). Around this same time, a popular game called pall-mall, a game similar to modern day croquet, appeared. Due to the rise in popularity of this game, a double allée of trees was planted outside the walls of Paris in order to provide shade for the players and also to mark the sides of the course (Lawrence 2006). The game spread within Europe, becoming so popular that courts and trees were popping up all around France and Italy. By the latter half of the 1600s the game's popularity waned, but the allées of trees remained and were repurposed for pedestrian promenades.

In the 1600s, the allée concept of tree planting had migrated from use outside city walls into use within cities. These allées were used throughout France for both pedestrians and vehicular traffic, as well as in the Netherlands along canals and adjacent streets (Hauer et al. 2017). In 1616, a 1,500-meter promenade called the Cours-la-Reine was constructed along the Seine river in Paris and planted with four rows of elm trees (Forrest and Konijnendijk 2005). Paris also added tree-lined avenues that were planted with elms, plane trees, and horse chestnuts leading on axis from the Tuileries (Lawrence 2006). The city walls around Paris were later planted with trees and transformed into promenades by Louis XIV towards the end of the seventeenth century. The old defense walls were planted with four rows of elms, creating a large central space for carriages and side allées for pedestrians (Lawrence 2006) .

While Paris was continuing to institute urban tree planting, perhaps the grandest example of trees used in an urban setting during this time was at Versailles. The grand tree-lined boulevards were planted to serve multiple purposes, such as making the large buildings more pleasing to the eye, creating better access in days of celebration, and simplifying defense on days of riot (Pitt, Soergell II, and Zube 1979). The plantings within Paris and Versailles were so popular that other cities throughout France such as Toulouse, Bordeaux, Lyon and Montpellier started to plant their own boulevards and esplanades.

Other cities throughout Europe, such as Berlin, Cologne, Frankfurt, Amsterdam, Basel, and London, soon began to follow suit and added trees to their urban fabrics. In 1647, Berlin planted the Unter den Linden, a tree-lined boulevard, which ran from the Brandenburg Gate to the Opera House and is just under a mile in length (Forrest and Konijnendijk 2005). With the popularity of the planted trees along the canals in Amsterdam, the city built a recreational area called the Nieuwe Plantage in 1682. Each of its squares were planted with a double row of trees (Forrest and Konijnendijk 2005), and astounded visitors who often described that they could not tell if they were in a city in a forest, or a forest in a city (Lawrence 2006). Basel, Cologne and Frankfurt started to plant trees in their town squares and in London, multiple public parks such as Green Park and Hyde Park began to open, providing recreational uses to the public. Due to industrialism in London, terrible urban conditions existed and these parks were seen as green lungs for the city and places of respite (Forrest and Konijnendijk 2005). Also in London, the Howland Great Wet Dock was built in 1703 and was lined with a double row of trees, one of the first examples of an industrial project to include tree plantings (Forrest and Konijnendijk 2005). It wasn't until almost 100 years later that trees began to make more appearances in the urban fabric of London with residential neighborhoods adding many series of squares planted with trees and lawns (Miller 1989).

While trees were starting to expand into more areas of cities, they were still for the upper classes of society, and mostly used in one of two ways. First, they were used in spaces for public activities, and second they were used by extension of private gardens situated in the cities, where wealthy residents could afford to place them on their property (Lawrence 2006). By the 1700s, other classes started to demand more access to the amenities that trees provided, and developers of the time saw that the inclusion of trees and open spaces could add market value to properties. Thus, residential areas started to see the inclusion of more trees within their developments (Hauer et al. 2017).

Paris, as well as the French Baroque garden movement, would have a profound impact on the layout and design of future cities and the inclusion of trees. The layout of Paris and its tree-lined boulevards, parks and parkways became the model for cities such as Detroit, San Francisco, Los Angeles, St. Louis and Minneapolis (Pitt, Soergell II, and Zube 1979). The baroque gardens would often have radiating paths lined with trees, which were used as inspiration for villages and towns in the 1700s (Miller 1989). The tree-lined paths and patterns of the gardens were envisioned to be the ideal street layout, which went on to inspire one of the most famous designs in 1791 - Washington, D.C. (Pitt, Soergell II, and Zube 1979).

While Washington, D.C. remains one of the United States' most important street layouts, it was not the first time that urban trees were intentionally placed with a design motive in the United States. In fact, for hundreds of years prior to the layout of Washington, pioneers and immigrants to the country brought with them the desire for tree-lined streets and avenues. In Cambridge and Boston, restrictions and ordinances around tree removal were written as early as the 1630s (Hauer et al. 2017). In colonial New England, village greens were the central point of early villages. While these spaces were initially intended for practicality and function such as keeping livestock and mustering militia, they were later planted with trees and landscaped (Miller 1989). In the city of Philadelphia, designed in 1682 by William Penn, five open spaces, each measuring between five and ten acres, were originally conceived to be filled with trees.

The concept of trees in cities in the United States was still so new at this time that it wasn't until the 1700s that insurance agencies would allow homes with trees to have insurance (Lawrence 2006).

In New York, some of the first instances of street trees came around the late 1600s to early 1700s. Presumably brought over by the immigrants who wished to have a little piece of the Netherlands with them in their new settlements, they first appeared in the Dutch neighborhoods. A mention of street trees within the city council is recorded in April 1708, when it was determined that residents of the Broadway of the city had the liberty to plant trees in front of their respective houses (Lawrence 2006). A map of the city of New York in 1731 also shows the appearance of street trees along the west side of lower and upper Broadway (Lawrence 2006).

In the late 1700s, the city of Philadelphia experienced a sharp increase of street tree planting. The Lombardy poplar was the latest fad in tree planting; not only was Philadelphia embracing it, but much of the rest of the country was planting it where possible (Lawrence 2006). Due to its quick growth rate, the poplar was able to transform many streets and towns in a relatively short time frame. Other examples of cities planting the poplar were in New York, where it was placed along the Battery, and in Washington, D.C., where Thomas Jefferson had plans to line Pennsylvania Avenue with the tree when he was president (Lawrence 2006). Although the Lombardy fad did not last long, their impact and use in the early days after the United States' independence had a ripple effect for future urban design. Due to their popularity, and their ability to grow where some other species may not have been able to survive, they were able to pave the way for street tree design which has survived to this day.

Aside from the desire of Americans to see street trees in their cities and towns, some early tree policies were written in the late 1700s and early 1800s. New York created a policy in

1799 which allowed street trees to be planted on any street wider than forty feet (Lawrence 2006), while Detroit passed an act in 1807 which called for a double line of street trees along both sides of 120-foot avenues (Reps 1965). In Mississippi, when selecting a capital in 1821, those in charge recommended that every other block be filled with vegetation native to the area or be planted with trees (Miller 1989). In Georgia, Savannah became an early model for street tree development. The original plan laid out by James Oglethorpe in 1733 called for wards built around open squares in the center. In 1790, there were eight of these wards and fifteen by 1814 (Lawrence 2006). As the city continued to grow in the following years, more wards were added, along with more street trees, mostly in double rows. A visitor to the city in 1820 wrote that "its streets, wide and straight, all cross at right angles, and are planted on each side with rows of very handsome trees…" (Lawrence 2006).

In the 1800s, the United States was witness to three landscape movements which would influence major cities around the country, as well as the concept of urban forestry: the City Parks movement, Romanticism, and the City Beautiful movement (Hauer et al. 2017). The City Parks movement, credited to Frederick Law Olmstead, sought to bring more vegetation and landscape into the urban fabric of the country. Romanticism came to landscape design as cities started to industrialize and more people began moving to the outskirts and looking for more natural and calming patterns of street layout. The City Beautiful movement was started, in part, due to the Columbian Exposition of 1893. Here, the grounds featured many tree-lined pathways both for vehicular and pedestrian access, as well as parks and boulevards, and architecture of Greek and Roman inspiration (Hauer et al. 2017).

Around the mid-1800s, many cities in the United States were experiencing massive urban population growth. New York's population grew from 131,000 to 643,000 between 1820 and 1850, a rise of almost 400%. Philadelphia and Baltimore's population both grew at over

150%, with Boston's growth over 200% and New Orleans' over 300% (Lawrence 2006). These rapid growths helped to bring trees into the cities, as well as create residential districts and public parks.

At the end of the 1800s, tree plantings occurred in multiple cities throughout Europe and were becoming a global element of design. Napoleon III kept transforming Paris with more tree-lined boulevards and public parks and squares, while other European cities followed suit. In Thailand, King Rama V planted trees along major streets in Bangkok (Hauer et al. 2017). Within the United States, Arbor Day was founded and first observed in Nebraska in 1872. On its first Arbor Day, Nebraska saw over one million trees planted (Miller 1989). Today, Arbor Day is still a celebration held every April and celebrates the planting of millions of trees throughout the country. Due to programs such as Arbor Day, as well as city planting initiatives and policy updates, urban tree cover within the United States has risen from over 16.5 million acres in 1990 to over 23.7 million acres in 2010 (Nowak et al. 2014). While that number may seem like a lot, the average coverage of urban tree canopy within the United States is only 27% (Nowak, Crane, and Stevens 2006). Total tree coverage within the United States is a bit higher at just over 34%, with states ranging from as little as 2.6% coverage in North Dakota to almost 90% coverage in New Hampshire (Nowak et al. 2014)

Trees have always had a special connection with the city of Atlanta. Sitting at the doorstep to the Appalachians, the forests help to blanket the city with old hardwoods and tall pines. While droughts have been the cause for recent tree losses in the city, other factors have been at play which have stripped the woods of their character. As a result of the city's recent growth and metro sprawl, nearly 50% of the region's tree canopy has been removed since the 1970s (Vargo 2014). Even so, a recent study still showed that Atlanta has one of the highest tree canopy densities and most overall regional tree cover (Nowak, Greenfield, et al. 2013). With

Atlanta's urban area growth of more than 250% from 1973 to 1999 (Vargo 2014), the forests have been badly damaged. Within that time frame, urbanization claimed some 600,000 acres of trees. Even with that loss, in 2001, American Forests estimated the value of Atlanta's forests to be roughly $2.5 billion, with some benefits ($86 million for storm water) accruing annually (American Forests 2001). It is estimated that during the 1990s, when the metropolitan areas of Atlanta were expanding quickest, if a more urban pattern of development was followed, up to 50,000 acres of trees could have been preserved (Vargo 2014). From 1985 until 2013, Trees Atlanta planted close to 88,000 trees within Atlanta. Within that same time frame, analysis from the University of Georgia estimated that growth in and around the city removed close to 50 acres of tree canopy per day. With this amount of removal, the number of trees planted by Trees Atlanta would be equal to what was lost in less than a month (Vargo 2014).

In a 2014 study assessing the urban tree canopy in Atlanta, the city saw 47.9% of its land covered by urban trees. The same study concluded that non-vegetation areas such as buildings, pavement, or bare earth covered 30% of Atlanta. In these findings, the least tree covered area of Atlanta was downtown, with less than 5% canopy coverage. This is understandable due to the higher density of buildings and man-made surfaces found within that area of the city. With added impervious surfaces in downtown and other commercial areas in the city, it would be difficult to add to this low percentage of coverage due to limited planting space available. Also noted in the findings was that 77% of the tree canopy within Atlanta was located on land zoned for single-family residential. Multi-family residential accounted for the second highest coverage within the city with just 8% of the total tree canopy, however only 37.3% of all land zoned for that category had tree coverage, leaving a large majority either impervious or without canopy. Other major zoning classifications studied included industrial, which only had 25% of tree coverage, and commercial, with just 20% coverage. (Giarrusso and Smith 2014)

The city of Atlanta's department of planning has a link on their website which allows anyone to view recent history of tree removal and replanting. The yearly reports only date back to 2014, however since then over 100,000 trees have been removed due to construction and urban growth (City of Atlanta 2020a). Slightly over 50% of that number fall into the category of dead, dying, or hazardous (DDH), so these trees are not counted as part of the total percentage loss compared to replanting. The number of trees removed that do not fall into the DDH category since 2014 is 49,931. In the same time, replanting efforts have not equaled those of removal, with only 45,922 trees replanted. This equates to a 92% replacement value (City of Atlanta 2020a).

There is no way to know how many of the DDH trees were actually dead versus how many were still healthy yet deemed hazardous, so it is difficult to put a total replacement rate on all of the healthy canopy recently lost. Just going by numbers, with only 45,922 trees replanted and 100,609 lost, the city has only managed to plant back 45.6% of trees removed over the past seven years.

One topic of future research is that of forest resilience. The climate is changing, so developers, planners, landscape architects, and researchers should be asking the question of what should be replanted now in order to better prepare for the future. Future climate predictions require more thought to replanting that simply replacing a like for like tree. Trees removed from urban areas planted 20, 40, 60, or more years ago may not be the same species which can survive in the next 20, 40, or 60 years. One study suggests that, when replanting forests, seeds should be moved 500 feet uphill (North, Millar, and Wright 2018). This is due to the fact that current species may not be able to thrive as well in warmer temperatures recorded, or may not be able to provide their full range of ecosystem services due to the climate. This will ultimately help to prepare for shifting climate zones and can ensure that replanting efforts stay in line with future climate models.

While any replacement is better than none, the majority of replacement trees are significantly smaller than those removed for construction. Due to this, the ecosystem services provided by the newer trees will take some time to catch up to the rate of services provided by the more established trees. For example, while it is found that a red maple (*Acer rubrum*) can average almost 4,800 gallons of stormwater intercepted a year, the bulk of that average happens later in its life, with a 5-year-old red maple only able to intercept slightly less than 200 gallons a year (McPherson et al. 2006). The same is true with pollutant capture. A 5-year-old red maple is found to be able to sequester around 40lbs of CO_2 per year, whereas a 40 year old red maple can sequester around 740lbs (McPherson et al. 2006). While this by no means is meant to discourage tree planting efforts, it goes to highlight even more the setback which occurs due to tree canopy loss in urban areas.

By using the Landsat Explorer app via the Change Matters tool from ESRI (ESRI 2020), the following images help to illustrate the tree canopy loss for the city of Atlanta since 2000. This app utilizes satellite imagery captured every 16 days in order to visualize change which can occur in vegetation, urban areas, water, or other areas of study. Vegetation coverage of Atlanta in September 2000 (Figure 5) and September 2019 (Figure 6) are shown below. While the image from 2000 just shows a dark green mass, the 2019 image places a light green color over the dark green in order to better visualize the change in vegetative cover. The difference in coverage is isolated and shown in red (Figure 7) to help understand the loss which has occurred. These images support the tree loss numbers from the City of Atlanta Department of Planning, as well as earlier statistics on tree loss during the early-2000s as a result of Atlanta's urbanization growth.

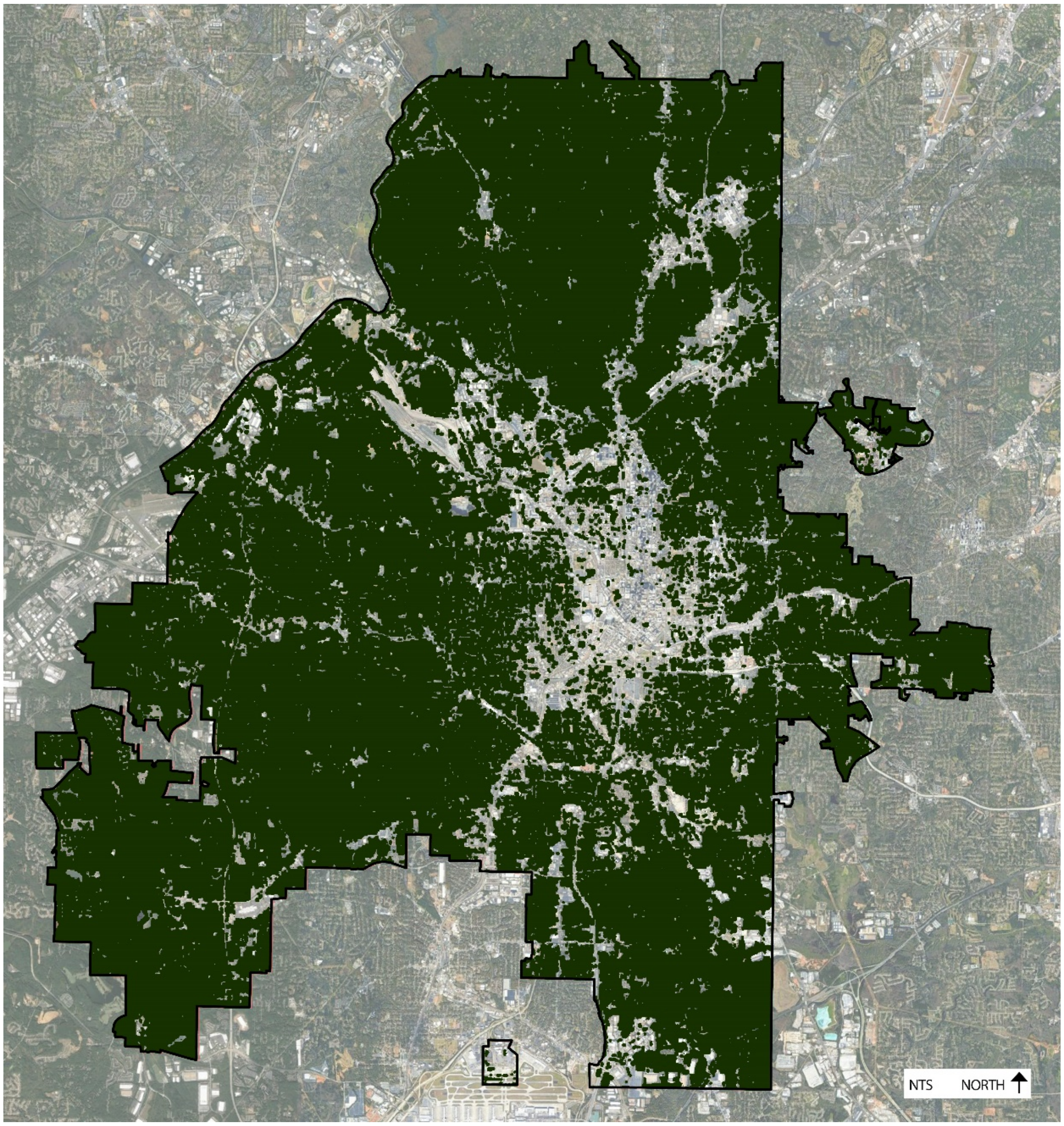

Figure 5: Vegetative coverage in Atlanta in 2000.
Sources: (ESRI 2020); (Google 2020b).

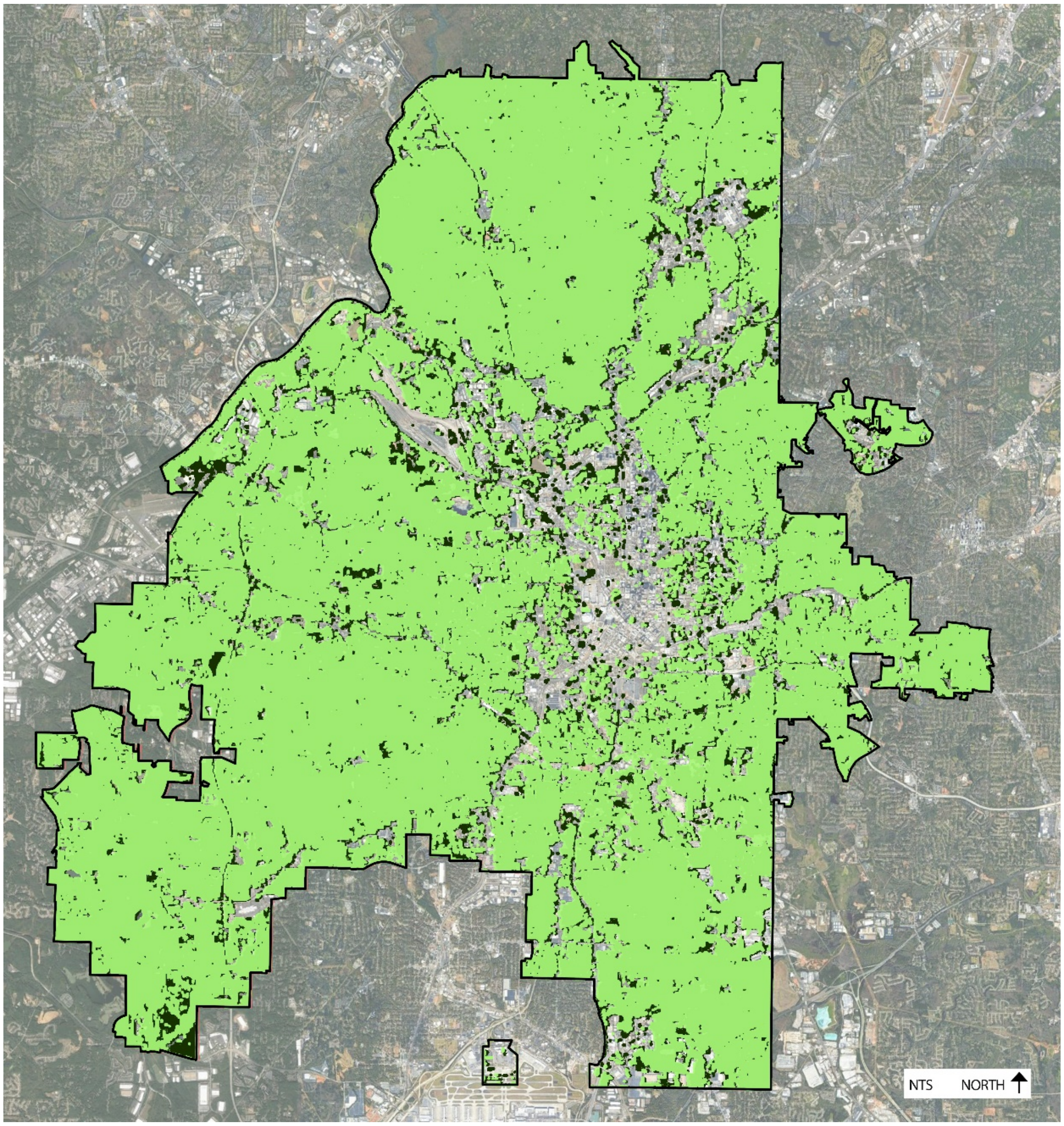

Figure 6: Vegetative coverage in Atlanta in 2019. Vegetation coverage from 2000 shown in dark green below to illustrate loss.
Sources: (ESRI 2020); (Google 2020b).

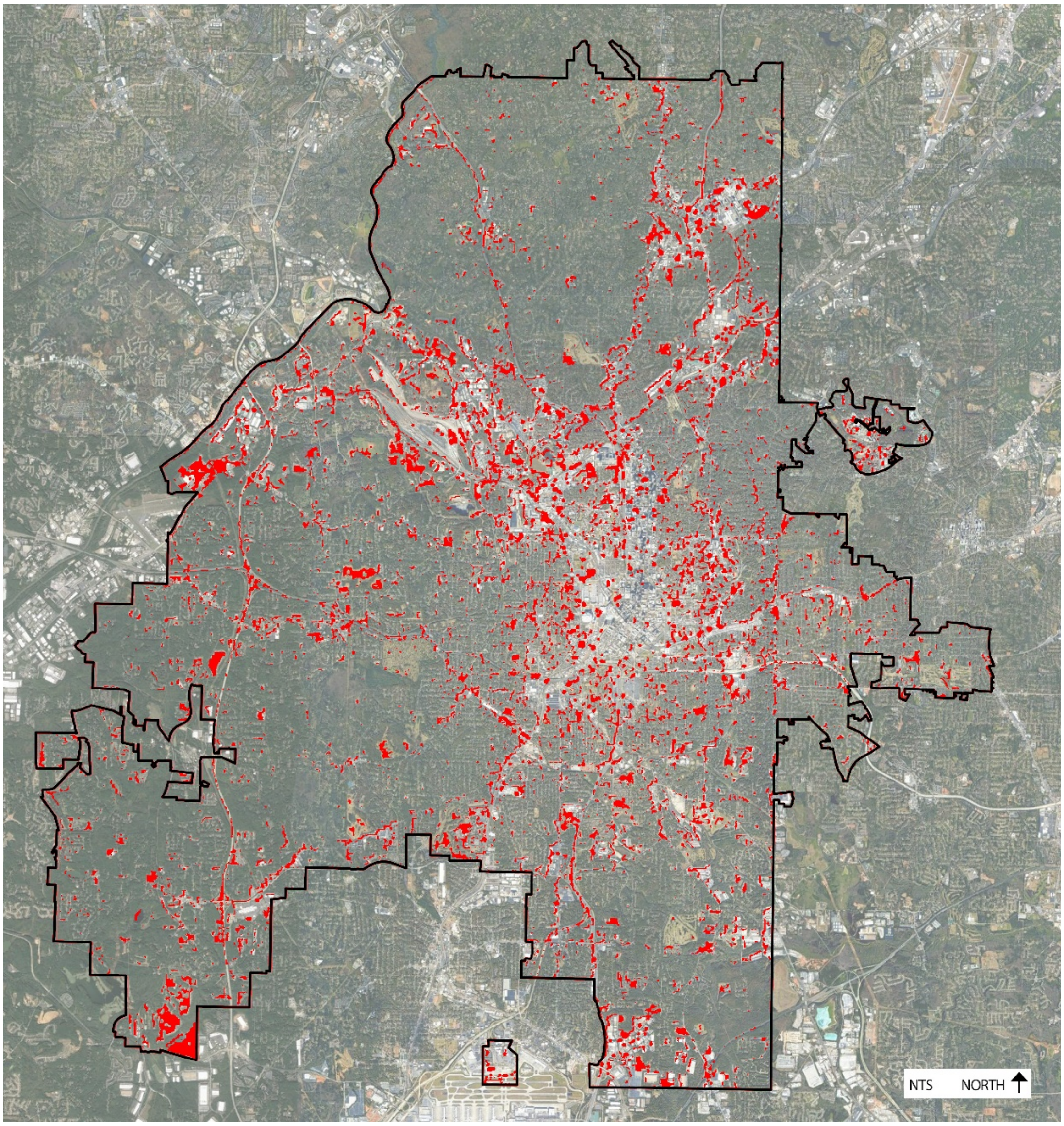

Figure 7: Vegetation loss in Atlanta between 2000-2019.
Sources: (ESRI 2020); (Google 2020b).

If Atlanta continues to follow the same patterns from the 1990s and early 2000s, the city will lose close to a quarter of the existing tree canopy. As previously highlighted, tree canopy is not the only thing that the city would lose. The ecosystem services provided by Atlanta's canopy are invaluable to the city. Through unchecked growth and development, Atlanta would be losing its natural air purifiers, channeling more stormwater into its sewer systems, and eliminating sources of cooler microclimates. While it may be easy to look at a group of trees removed for development as a small drop in the overall bucket that is Atlanta's canopy, focus needs change in order to see them for their benefits to the ecosystem and region as a whole. Using the knowledge of past urbanization periods, Atlanta can identify smarter ways of growth which can help preserve its canopy, maintain the status as a city in the forest, and steward the land for future generations.

The twentieth century continued to be a big step in the history of urban trees. Cities and towns all across America saw the continued development of urban parks, squares, green belts, and tree planting programs (Hauer et al. 2017). Today, street trees and street tree policy are a major part of many city ordinances. Developers and pedestrians alike see the environmental benefits that trees bring to urban centers, thus they are planted just as much for these benefits as for public enjoyment. It is our responsibility to continue the advancement of trees within the urban fabric, as they enhance cities and bring about invaluable positive effects to the environment.

History of Vegetated Roofs

Just as trees add a valuable aspect to the green infrastructure of cities, so do vegetated roofs. The main difference is that while trees have been used throughout the urban fabric for hundreds of years for environmental purposes, vegetated roofs are relatively new when it comes to their environmental uses within cities and urban areas. Before detailing the individual environmental benefits of vegetated roofs, it is important to understand their uses throughout time, from private gardens to social spaces and city green infrastructure.

While vegetated roofs may seem to be a more recent or even developing technology, their origins date back thousands of years. Since ancient times, man has built sacred sites such as religious monuments, memorials, and homes which have incorporated some form of vegetation over elevated surfaces (Weiler and Scholz-Barth 2009). From Ireland and Scotland, where Neolithic dwellings were built into the hillside, to Scandinavian and Kurdish-speaking countries where homes were constructed with pitched sod roofs (Velazquez 2012), vegetated roofs have taken some form or another throughout the past. In those times, the roofs were more about using the surrounding landscape for shelter and insulation rather than for decoration or environmental purposes. Turf grass roofs were typically constructed over birch bark, twigs, or straw, and also helped to keep rainwater from entering the home (Dunnett and Kingsbury 2008). These roofs somewhat mimic the modern day extensive vegetated roofs. The earth and sod provided shelters which were relatively warm in the winters, while also being cheap, as the materials were readily available. In the Kurdish-speaking countries, such as Turkey, Iraq and Iran, turf roofs not only helped to keep the home warm in the winter, but also helped to keep the hot sun out in the summer (Dunnett and Kingsbury 2008). Not only were these roofs constructed in Scandinavia and the Middle East, documentation also shows examples from further east in China and Japan. In Japan, where traditional thatch roofs could be damaged by the abundance of rainfall, plants were added in order to help strengthen the integrity of the roof (Dunnett and Kingsbury 2008). North America was introduced to the concept of sod roofs when settlers first came to Nova Scotia and later made their way into the prairies and used the concept of turf roofs on their homes (Velazquez 2012).

While the use of local materials and earth were implemented for these dwellings, the emergence of roof gardens was also occurring simultaneously throughout the Middle East. These gardens, unlike the homes in Ireland, Scotland, and Scandinavia, were built on castles, monuments, or private estates for personal or religious glorification rather than necessity. One of the oldest examples of these gardens is in Iraq. Built around 2100 BC, the Ziggurat of Nanna was a stone structure which is believed to have had trees and shrubs planted along its terraces (Velazquez 2012).

Perhaps the most famous roof garden of ancient times, and possibly the most famous in history, was the hanging gardens of Babylon. So famous are the hanging gardens that they are known as one of the seven wonders of the ancient world. They were constructed around 600 BC by Neo-Babylonian King Nebuchadnezzar II and utilized a checkerboard style layout which was so large and covered in earth, that the gardens could accommodate the largest of trees (Dalley 2013). The gardens, which still remain somewhat of a mystery today, were described by historians as having a series of vegetated terraces consisting of flowering and fragrant trees, shrubs, and vines (Velazquez 2012). It is thought that King Nebuchadnezzar II had the gardens constructed and so elaborately planted in order to resemble the hills in Media, where his wife was from (Dalley 2013).

Early first-hand accounts of vegetated roofs exist, where in 1805 Chinese writer Fu Shen described being outside of Huancheng's city walls at a place called Wang's Garden:

> The piece of ground on which it stood was broad from east to west, but narrow from south to north, because on the north it backed up directly on the city wall, while to the south it abutted on to the lake. This limited area presented many problems of design which I found had been solved by building the garden according to the methods of doubled terraces and storeyed halls. By doubled terraces I mean that the terraces on

> top of the buildings were extended into hanging roof gardens, and rocks arranged and flowers planted up there so that a visitor would never know that a building lay beneath his feet. (Shen, Pratt, and Jiang 1983, 137-138)

Shen further described small ponds which were located throughout the gardens and mentioned that the design was “such that a visitor could hardly tell what was illusion and what was reality” (Shen, Pratt, and Jiang 1983).

In the late nineteenth century, European countries were some of the first to begin widespread research and propagation of vegetated roofs, which happened almost accidentally. During this time, roofs were constructed out of wood and tar-board. The tar-board was then covered with sand and gravel for fire prevention purposes (Werthmann 2007). Over time, these roofs started to sprout random vegetation, which in turn started to interest researchers about the benefits and uses of vegetated roofs in the region. At the same time, Eduard Rüber, who was the head of the building department in Munich, Germany, began to see the economic and environmental benefits of vegetated roofs and started to propagate grass roofs in the 1860s (Werthmann 2007). Later that decade, in 1868, the Paris world exhibition included a nature roof as a part of its showcase (Dunnett and Kingsbury 2008). Also, in the late nineteenth century, other major cities such as London, Paris, and New York City installed their own rooftop gardens. These were designed more for the people and to be a small bit of nature to escape to within the large cities. In New York City, some of these roofs became very popular when some of the theaters started hosting concerts and musicals in these gardens (Velazquez 2012).

At the start of the twentieth century, one piece of technology, the invention of the flat roof, allowed roof gardens to become more widespread. This technology allowed everyone potential access to a garden in the sky, no longer a luxury solely for the wealthy. Due to this increase in ability for rooftop garden construction, design thought started to wonder what the future would look like. One German landscape architect predicted that “man will stroll from roof garden to roof garden which will continuously crown the tops of our cities as sunlit and flowering paradises” (Werthmann 2007). One of the most famous architects of the time, and of the modern era, Le Corbusier, even started to incorporate some roof gardens into his architecture, claiming them to be a “fifth façade” (Cantor and Peck 2008).

Around the 1920s, the popularity of New York City’s rooftop theatre productions had started to diminish. Instead, many hotels and restaurants started to add rooftop dining experiences, where possible. These rooftops provided a place for patrons to dine outside in the city, offering views not available at ground level. Some were adorned with fountains, potted shrubs, trees, or vines (Velazquez 2012).

In the late 1930s, London completed one of the largest rooftop gardens atop the Derry & Toms department store in Kensington. Known today as the Kensington roof gardens, they were built 100 feet above the high street and were designed to emulate Spanish gardens, looking to transport some of the warmth of Spain into the middle of London (Peel and Bolitho 1960). A further two gardens then opened on the roof, bringing the total size to just over one and a quarter acre. The gardens featured wide walks, a flowing stream, flowers, shrubs, and large trees rising some thirty feet above the rooftop. They were so popular that they were described as being “one of the wonders of horticultural England” (Peel and Bolitho 1960).

Aside from the Derry & Toms rooftop, development of vegetated roofs slowed drastically between the late 1920s and 1960s. This was first due to the Great Depression, which forced a stop to all added building amenities. Then, when the economy started to rebound, the development of air conditioning was becoming more common and affordable, which seemed to negate the need for the cool oases in the sky. Coming into the 1950s and 1960s, Germany and other German-speaking countries in Europe kickstarted mass vegetated rooftop design. This was helped by the wider movement which recognized the value, both ecological and environmental, of urban habitats (Dunnett and Kingsbury 2008). Gone were the days of timber and tar-board roofs. Construction of flat roofs usually had a gravel topping, which spurred more random vegetation and urban habitats for birds and other wildlife. When the counter-culture movement started in the 1960s, people began to experiment with what was described as 'greening the city' (Dunnett and Kingsbury 2008). Inspired by new ways of thinking and experiencing the environment, settlements started to take over major areas of large cities, such as Berlin.

Throughout these areas, plants were grown in containers which sprouted on flat roofs, vegetables were placed in planters on roofs and terraces, and community gardens started to arise. Due to this, experiments began to research the practicality of growing plants within substrate layers on roofs. Germany and Switzerland put this idea into practice when, in the 1960s and 1970s, they started developing Terrassenhauser, whereby homes were built on steep gradients and the roof of one lower home would serve as the garden for another higher home (Dunnett and Kingsbury 2008).

Environmental movements of the 1970s brought about research which concluded that vegetated roofs bring about many benefits, especially energy conservation and the ability to reduce water runoff. This is one of the first examples of tangible environmental and economic benefits happening due to the implementation of vegetated roofs. Also, during this time, the publication of several books on the topic of vegetated roofs saw authors arguing for the benefits of vegetated roofs to the urban environment. These events all helped the concept of using vegetated roofs as a sustainable building technique arise (Velazquez 2012). With rooftops now topped with gravel, the addition of a thin layer of soil to them further aided the implementation of these early vegetated roof prototypes.

In Germany, the entire environmental movement climaxed in 1975 with the formation of the Research Society for Landscape Development and Landscape Design (*Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau,* FLL). They released their initial guidelines into roof greening in 1982, and subsequently aided to advance the eco-movement of the 1980s (Werthmann 2007). The FLL is still influential in the field of vegetated roof design to this day and frequently updates their guidelines as well as providing definitions, testing, and standards for the industry (Velazquez 2012).

Around the same time that the FLL was starting to issue their guidelines, the German Green Party was becoming influential in parliament. Their rise helped to guide vegetated roof policy within Germany, with some cities such as Stuttgart implementing mandates to help with the city's temperature and water pollution. This was partly driven by the ecological benefits, but also due to the discontent of the then current aesthetic of the built environment (Werthmann 2007). Dismayed by the sight of bare flat roofs, the people of many German-speaking countries in Europe began to experiment with different methods of construction. One such method was removing the gravel on top of the roofs and substituting a thin growing medium. Due to the low weight of the soil, no additional structural support was needed and costs were kept relatively low. Since these roofs were not meant for any social functions and fully covered with vegetation, it was determined that they provided similar benefits to those of traditional roof gardens. They helped to filter and clean rain water, reduced noise level in the buildings, insulated against the heat, cooled the surrounding air, provided habitats for animals, and helped to extend the life of the roof (Werthmann 2007). This was the start of the modern extensive roof, and the technology has since taken off and provided a solution to many problems that have arisen due to urban densification, such as water pollution, air pollution, and the urban heat island effect.

Since the rise of Germany's influence in the world of vegetated roofs, they have maintained their status as the center of vegetated roof activity in the world. They have embraced laws and policies around implementation, such as the Federal Nature Protection Act and the Federal Building Code (Dunnett and Kingsbury 2008). Today Germany has forty municipalities throughout the country which either encourage, mandate, or incentivize the use of vegetated roofs on construction. Through these policies, nearly five square miles of green roofs are constructed in the country per year, a size equal to over 2,000 football fields or four Central Parks (Werthmann 2007). In contrast, Green Roofs for Healthy Cities reported in their 2016 annual market survey that the total square footage of vegetated roofs installed in the United States and Canada combined was just over four million (Stand and Peck 2017). Although this was still a 10% growth from the previous year, the total square footage equates to just over .14 square miles, or roughly three percent of the total square footage from Germany.

Around Europe, other countries are also starting to implement more vegetated roofs. London, England is constructing large areas of rooftops gardens for bio-diversity and Malmo, Sweden built a botanical roof garden which provides for demonstration and research into the range of green roof types and performance (Dunnett and Kingsbury 2008). Some of the southern countries in Europe have been slower at vegetated rooftop development, such as Greece, Spain, and Italy. This could be for a number of reasons such as the different climate they have over northern countries like Germany, Scandinavia and the United Kingdom, or overall public opinion. Some feel that if money is to be spent on a vegetated roof, especially in countries such as Greece that have a weaker economy, then the roof should be accessible to the public (Dunnett and Kingsbury 2008). In other countries, such as Russia, vegetated roofs have proven useful as agricultural spaces, providing a way for food production in an urban environment where residents may not have access to land outside of the city.

Even though the United States has lagged behind some European countries when it comes to vegetated roof implementation, each year they are making further improvements. In 1998, Chicago's mayor visited Germany to visit some of their vegetated roofs. Upon his return, the city of Chicago implemented several initiatives around vegetated roof development and in 2000, completed a 20,000 square-foot retrofit of city hall, which was a first for a municipal building in the United States (Velazquez 2012). Along with Chicago, other cities such as Portland, Washington, D.C., and New York City are also starting to implement more vegetated roofs each year. With such diverse climate zones within the United States, there are ample opportunities for even more cities to begin vegetated roof development. While vegetated roofs have been in this country for over one hundred years, it was not until 2005 that their development really took off. In that year alone, the United States saw a 70% increase in vegetated roof development, with over 2 million SF planted (Werthmann 2007). At that time, even with over 2 million SF planted, the United States still only could claim around 0.01% of the world's vegetated roofs. In the years since, they have continued to trend upwards, with an estimated 17.5 million total SF of vegetated roofs in 2016, but are still not close to Germany, who claim close to 8% of the world's vegetated roofs (Werthmann 2007). The United States sees a staggering number of rooftops either newly built or renovated every year, averaging over 930 square miles (Werthmann 2007). That is more than six times the size of Atlanta. If only five percent of these roofs were covered with vegetation, there would be 46.5 square miles, or 29,760 acres, of vegetated rooftops implemented per year, which would make the United States one of the top countries in the world for vegetated roof development.

Even though vegetated roofs have been around for thousands of years throughout the world, the United States is still in its infancy in their development. By learning from past trends, policies, and designs, more informed decisions can be made about the best way forward for vegetated roof implementation. While Germany is still ahead of the United States in terms of development and policy, the United States has the resources, climate, and knowledge to become a world leader in the vegetated roof market, perhaps sooner rather than later.

Vegetated Roof Policy Around the World

As this thesis has discussed, vegetated roofs aid in multiple ecosystem services. Their main contributions are to the regulating services, such as reducing the UHI effect, capturing and retaining stormwater, removing air and water pollutants, and mitigating greenhouse gas emissions through reduced building energy consumption. Not only these, but vegetated roofs also contribute many cultural benefits through regulating building temperatures, providing the ability to install urban farming, or offering added greenspace in areas previously without. Other benefits can include increasing local biodiversity, improving viewsheds, providing a green oasis in urban areas, and adding real estate value, all while being situated on what has historically been thought of as valueless real estate (Joslin 2018). The last benefit is of particular note, as the added value brought about by green infrastructure is also known as natural capital. This is a term which recognizes that there is a monetary benefit to ecosystems and is thought of as the most important form of capital, for it provides basic necessities for existence (European Environment Agency 2020).

For the past 30 years, the United States has become more educated on the added value and benefits of vegetated roofs. As this has progressed, each year more cities have started to implement policies, incentives, ordinances, or mandates to include vegetated roofs in new construction. This section of the thesis will examine different types of vegetated roof policies and mandates, as well as some of the cities which have implemented these policies.

Key environmental issues within cities such as increased stormwater runoff, an existing lack of greenspace, rising UHI, or increased roof reflectivity typically drive the implementation of vegetated roof policy. Policy around green infrastructure and vegetated roofs generally tend to fall into one of three categories: pilot projects, incentives, or mandates (Malina 2010). Pilot projects are usually started by the city municipality on public buildings and are implemented to help showcase feasibility and results of the vegetated roof. Incentives help to keep costs low for developers, as high costs are often one of the main reasons for not developing vegetated roofs. Mandates can require the development of vegetated roofs through technology or performance standards. Incentives and mandates, also known as the carrot and the stick respectively, differ in the fact that incentives help encourage markets to emerge while mandates establish markets (Joslin 2018). Incentives do not guarantee construction of vegetated roofs, they merely offer enticing bonuses to those properties which elect to construct vegetated roofs. Mandates provide the most guarantee for the inclusion of vegetated roofs, as local governments can dictate policy and standards, however they are often harder to pass.

Sub-policies exist within these categories, which can include: density and floor area ratio (FAR) bonuses; grant, rebate, or subsidy funding; stewardship programs; stormwater fee credits; tax credits; green area factor; and procurement (Stern, Peck, and Joslin 2019). Another branch of incentives is through green building credits, which vegetated roofs can help to bring through their implementation on projects. In a survey with industry professionals, the ability to secure green building credits was one of the greatest opportunities cited through the survey (Tabatabaee et al. 2019). Policies are sometimes based upon the climate or location of the city. For example, whereas a wetter city may incentivize more stormwater credits and a warmer city may issue policy regarding the reflectivity of the roofs.

All of these sub-policies tend to fall into one of two groups: direct or indirect incentives. Subsidies and grants, for example, help to mitigate the initial cost of installation and would fall under the direct incentives. FAR bonuses, fee credits, or permit fast-tracking are all examples of indirect incentives and offer owners and developers returns if the vegetated roofs are implemented (Malina 2010). Direct incentives can be preferred due to the fact that they offer direct compensation for a percentage of the construction of the roof. Being that often the construction costs are the most inhibiting factor when it comes to implementing vegetated roofs, these can be appealing to developers and building owners (Timothy Carter and Fowler 2008). Indirect incentives are more common, even though they might not be the most preferred from a developer or owner standpoint. These incentives can come in the form of municipalities issuing credits for stormwater utility fees or building density bonuses (Timothy Carter and Fowler 2008), however they can vary from year to year due to municipal budgets fluctuating and grants or subsidies running out. One important factor for policy is that incentives are only able to work properly if the benefits are equal to or outweigh the costs. If the policy is not strong enough or does not provide enough rebates or credits, there is often little interest in developing a vegetated roof due to the added installation costs when compared to a typical bare roof.

International Policy

In remembering the history of vegetated roofs and the importance of Germany in their growth and development, it should come as no surprise that they are also at the forefront of vegetated roof policy throughout the world. Today, almost half of all German cities offer vegetated roof subsidies (Timothy Carter and Fowler 2008) and due to grants, incentives, and mandates, Germany can boast that between 15-20% of the country's roofs are vegetated (Malina 2010).

The German government supports vegetated roofs at the federal, state, and local levels. Although these vary from location to location, most municipalities promote the use of vegetated roofs through either construction subsidies, stormwater discounts, or local development requirements (Dunnett and Kingsbury 2008). Since the 1980s, it has been common in Germany for owners to be charged for stormwater management. This is a separate charge from normal drainage fees, and is one reason for the development of vegetated roof policies early on in the country. Vegetated roofs generally qualify for a discount between 50-100% of the stormwater fees and because of this, roofs are able to pay for themselves over the course of their lifetime.

One of the first German cities to begin supporting the development of vegetated roofs was Stuttgart. Their Green Program for Urban Renewal was instituted in 1980 and gave subsidies for material and installation costs, as well as free advice from city departments (Dunnett and Kingsbury 2008). Shortly after, Berlin began instituting policies and encouraging the construction of vegetated roofs. In 1988, the city required that if a building took up too much ground space, the developer would have to construct a vegetated roof in order to complete construction (Dunnett and Kingsbury 2008). Between 1983 and 1997, West Berlin reimbursed 50% of construction expenses for vegetated roofs and saw the addition of close to 700,000 SF of them throughout the city (Malina 2010). In the 1990s and 2000s, other major cities throughout the country, such as Munich, Dusseldorf, and Karlsruhe, adopted policies of their own, following the examples in Stuttgart and Berlin. In Berlin today, the city uses a Biotope Area Factor (BAF) in order to determine how much green space a development should have within its property. This is calculated as a ratio of greenspace to the total site area. Because of the BAF, it is common in many zones of the city to see vegetated roofs used to fulfill the guideline (Malina 2010).

While many German cities remain world leaders in vegetated roof policy, many other cities throughout Europe are starting to implement policies of their own. In Copenhagen, Denmark, mandates require new roofs with slopes less than thirty degrees to be vegetated, which is an attempt for the city to become carbon neutral in the future. In Sheffield, England they developed a Green Roof Forum and by doing so became the first city in the United Kingdom to adopt a policy surrounding vegetated roofs. Linz, Austria requires that all new developments which do not have a minimum greenspace at ground level develop a vegetated roof and in Switzerland, federal law requires facilities to be compatible with natural settings and 25% of new commercial developments are to be greened in order to combat UHI and climate change (Dunnett and Kingsbury 2008).

Outside of Europe, vegetated roof policy is gaining momentum in other parts of the world as well. In 2001, Tokyo mandated that new buildings have 20% vegetated cover. Within a year, the city nearly saw a doubling of vegetated roofs, from 564,000 SF to over 1.1 million (Malina 2010). By 2005, the city had seen almost 135 acres of rooftops vegetated (Timothy Carter and Fowler 2008). Singapore is also starting to use vegetated roofs throughout the city, not just as a means to combat environmental issues, but also as a way to provide greenspace access in their small city for the large population. Other international vegetated roof policies can be found in Brazil, South Korea, Australia, and China, where Beijing offered subsidies on vegetated roof development before the Olympic games in 2008 (Dunnett and Kingsbury 2008). The city currently adds around 25 acres of vegetated roofs a year which is good, but in a city with close to 23,000 acres of rooftops there is still room for improvement.

North American Policy

Policy within North America has been slower to establish than some of its European counterparts. While many cities have started to implement more vegetated roof ordinances, the vast majority of North America is still without any policies. Over 400 jurisdictions have fees related to impervious surfaces, yet only 20 to 30 have dedicated green roof policies (Living Architecture Monitor 2016b). Three of North America's top cities in terms of vegetated roof policy development, and the subject of the majority of research, are Toronto, Chicago, and Portland.

Beginning in 2000, Toronto established a pilot project which invested money into vegetated roof test sites on the roofs of City Hall and a nearby community center. The goal of the pilot project was not only environmental, but also to raise public awareness about their benefits and to remove any information barriers that may have existed around technical or financial aspects of the roofs (Malina 2010). During the trial, the city allowed access to professionals so that they could learn about the sites and structures. Through these projects, it was concluded that if the city were to add vegetation to only six percent of its rooftops, temperature would decrease by upwards of 3.6°F, greenhouse emissions would be cut by 1.56 megatons, smog advisories would reduce between 5%-10%, stormwater retention would go up by almost one billion gallons (3,068 acre-feet), and energy savings would be close to one million Canadian dollars (CAD) (Malina 2010). This information helped Toronto become the first major city within North America to adopt mandatory requirements for vegetated roof development on new buildings. Through these results, as well as further studies into even larger vegetation percentages, Toronto has set out to be a showcase for the world in terms of vegetated roof initiative.

Since those first two pilot projects, Toronto has approved a policy stating that where feasible, all new City-owned buildings shall have vegetated roofs with coverage of at least 50%-75% of the building footprint (Timothy Carter and Fowler 2008). In 2006, the city set money aside for public use with a Green Roof Incentive Pilot Program, which gave property owners $10 CAD/square meter ($m^2$) of vegetated roof constructed, up to a maximum of $20,000 CAD (Malina 2010). That program has since grown and developed into the Eco-Roof Incentive Program, tailored for commercial, industrial, and educational buildings. This program offers $50 CAD/$m^2$ with a maximum payment of $100,000 CAD. Paying over $500,000 CAD in grant funding in 2009, the city continued to see interest in vegetated roof development as a result of the program. Shortly after, the city passed their mandatory requirement mentioned earlier, which states that all new buildings over 2,000 m^2 (21,527 SF) gross must cover between 20%-60% of their roofs in vegetation (Malina 2010).

Due to Toronto's incentive programs and vegetated roof requirements, the city has seen over 5.5 million SF of vegetated roofs developed since 2009. Annually, the city sees a reduction of over 58 million gallons (178 acre-feet) of stormwater, 225 tons of carbon sequestered, and over three million kilowatt hours (kWh) of electricity savings for buildings with vegetated roofs (Stern, Peck, and Joslin 2019).

Cities within the United States have been slow at developing vegetated roofs and policies surrounding them, but as their economic and environmental benefits are starting to show, more cities are creating policies (Velazquez 2012). Another reason for the kickstarted development of vegetated roofs is due to politicians, researchers, and developers traveling to Germany and seeing the success they are having (Dunnett and Kingsbury 2008). One example of this is from Chicago, which also happens to be one of the largest US cities for vegetated roof development. As previously mentioned, in the late 1990s, Chicago's then mayor traveled to Germany and was so inspired by the vegetated roofs there that upon arriving home, he set up a pilot project on the roof of Chicago's City Hall building. The 20,000 SF site is home to over 150 species of trees, shrubs and grasses and was implemented with the hopes of combatting the city's growing UHI. Much like that of Toronto, this pilot project helped the city to research the added benefits of vegetated roofs in order to implement policies, incentives, and mandates throughout the city.

By 2002, Chicago had passed an energy code which became the first ordinance in the United States to mention the use of vegetated roofs (Dunnett and Kingsbury 2008). In 2005, the city launched a Green Roofs Grant Program, which offered incentives to residential and small commercial developments. Owners could receive $5,000 USD to install vegetated roofs and within a year, the city had paid $100,000 USD for twenty different projects (Timothy Carter and Fowler 2008). A year later the grant program doubled, established into a Green Roof Improvement Fund, and was made to include owners and developers within the central business district. This fund allowed for reimbursement of 50% of vegetated roof costs if at least half of the rooftop was covered with vegetation (Malina 2010). Aside from funding incentives, the city has also allowed for building density bonuses with the installation of vegetated roofs. These incentives have allowed Chicago to become a leader in vegetated roof development and have added over 7 million SF of vegetation on over 500 rooftops (Velazquez 2012).

Alongside Chicago, Portland has been at the forefront of vegetated roof construction and policy within the United States. The city began experimenting with test plots of vegetated roofs after Tom Liptan, a city employee, became interested in the concept and built a small plot at his residence in the mid-1990s (Stiffler 2010). He collected data and brought his results to the city, which then began their own research. In 1999, Portland became the first city in the United States to fund test sites for ecoroofs (Malina 2010). The following year, the Multnomah County Building was replacing its roof and the city decided to create a larger pilot project for more research. Completed in 2003, the roof is 12,000 SF in size. The roof consists of wildflowers and grasses that help to mitigate stormwater runoff and ease sewer overflows to the Willamette River, which help to keep the local salmon populations healthy.

In 2001, Portland amended its Zoning Floor Area Bonus ordinance to include ecoroofs, which allows for one bonus square foot of building for each square foot of vegetated roof, if the vegetated roof covers 30% or less of the roof. For vegetation covering between 30%-60% of the roof, two bonus square feet of building can be added for each square foot of vegetation, and for vegetated roofs covering 60% or more of the rooftops, three bonus square feet are allowed within the building per square foot of vegetation coverage (Timothy Carter and Fowler 2008). In the first six years of this policy amendment, more than 120 vegetated roofs were constructed, generating $225 million USD in added private development (Malina 2010). Further policies were passed in 2005 and 2009, when the City Council required that all city owned facilities be outfitted with vegetated roofs when practical. This was passed to go along with the Portland comprehensive plan, which has a goal of 18% coverage (408 acres out of 2,267 acres) of rooftops by 2035 (Living Architecture Monitor 2016a).

In 1977, Portland started to charge property owners a fee for stormwater fees for discharges from their properties. Due to the success of the pilot project and the added knowledge about the environmental benefits of vegetated roofs, the city provided a stormwater incentive program in 2006 in order to reward developments which limited the amount of runoff from their properties. In the five years prior to the incentive, only 26 vegetated roofs were built for stormwater purposes. The year after the program started, 23 vegetated roofs were constructed (Timothy Carter and Fowler 2008). The incentive also allows for other methods of management, not just vegetated roofs. By the end of 2007, over 33,000 users had registered for the incentive. The city estimates that participation in the incentive will rise to over 100,000 of its 176,000 users (Malina 2010), helping to show the impact that green infrastructure policy can have on a city.

In 2008, Portland launched the Grey to Green Initiative, which was a five-year program with $55 million USD worth of funding. While the initiative also focused on street trees, green streets, and infrastructure repairs, one of the main goals was the addition of more vegetated roofs. The initiative helped fund vegetated roofs at a rate of $5/SF and saw the creation of almost 200 new vegetated roofs in the five years that the program ran, totaling almost 11 acres of space. Through all of Portland's incentives and policies towards vegetated roof development, the city today boasts almost 400 vegetated roofs at a total square footage of over 1.3 million.

While these are just three examples of vegetated roof policies in North America, many more cities are following suit. Austin, Boston, Denver, Minneapolis, Nashville, New York City, San Francisco, and Seattle are all examples of cities with either mandatory green roof requirements or incentives in place to promote their use. Washington, D.C. gives a $15 USD/SF incentive to projects helping to eliminate stormwater from the sewers. New York City passed the Climate Mobilization Act in an effort to reduce greenhouse gases and included a requirement for green roofs or solar panels on new construction. Minneapolis has a 100% stormwater fee credit which includes the use of vegetated roofs. Atlanta passed the Post Development Stormwater Management Ordinance in 2013 requiring sites to manage the first one inch of rainwater onsite through green infrastructure. While there is no requirement for vegetated roofs within the policy, they are an option and the ordinance is a good step in the direction of realizing the benefit which vegetated roofs could play within the city. Also called for in the Georgia Stormwater Management Manual is that runoff should be treated for 85% of storms annually and 80% of total suspended solids (TSS) need to be reduced. For larger storms, these statistics equate to treatment of the first 1.2" of rainfall (Atlanta Regional Commission 2016).

Lastly, although not a required policy, the United States Green Building Council (USGBC) has developed a green building rating system known as the Leadership in Energy and Environmental Design (LEED) rating system. This system is comprised of different types of credits which builders and developers can use in order to gain different levels of certification for their projects. While mainly used for building interiors and materials, vegetated roofs can contribute to a building gaining a higher LEED status. For example, vegetated roofs can help gain credits in the sustainable sites, water efficiency, energy and optimization, or materials and resources categories (Breuning 2020). Overall, vegetated roofs can greatly assist in LEED certification and can contribute to up to 20% of the overall credits needed for a LEED-certified project. While LEED certification denotes a project as being environmentally friendly, the policy is not mandatory in most jurisdictions and is up to the developer and owner to pursue. Another green building standard which give credits for vegetated roof implementation is Green Globes. This standard is administered by the Green Building Initiative and is also a voluntary system which encompasses all buildings except residential structures (U.S. Environmental Protection Agency 2019a).

Aside from the Post Development Stormwater Management Ordinance and possibility for green building credits through LEED, Atlanta currently has no policy, mandate, or incentive around vegetated roof development. One of the best ways in which to try to implement policy is through education and demonstration. Even with the advanced implementation costs of vegetated roofs, if the city were to strategically pick locations and implement test sites centered around popular areas or places where people congregate, ecosystem service benefits of vegetated roofs may be more widely recognized. This could lead to further test sites, private development, incentive programs, and policy adoption. Atlanta is such a transportation hub for the Southeast that one of the first places to start would be at Hartsfield Jackson International Airport. Airports are notoriously void of trees and covered in impervious surfaces. By having vegetated roofs on top of the terminals, millions of people annually would see them and could begin to wonder about their benefits on other buildings. Other rooftops which could be good candidates would be sports stadiums, arenas, convention centers, public transportation shelters or stations, restaurants, hotels, or malls. In order to get a stronger public opinion about the implementation of vegetated roofs and policy, developing them in places most visited by residents and visitors to Atlanta would be the best places to start.

Through research into international and domestic policy, one thing found is that vegetated roof policies are able to benefit so many different environmental issues. They aid in stormwater runoff, sequestering carbon and air pollution, lowering the UHI and roof reflectivity, providing new habitats, lowing energy costs, and raising property values. As highlighted in cities across Germany, Canada, and the United States, pilot programs and educational campaigns for owners, developers, architects, and elected officials could be what is needed to kickstart many more cities implementing policies around the country. The saying "think globally, act locally" really applies to vegetated roof policy. If more major cities took a serious look into implementing policy, the environmental benefits could be staggering.

Benefits of Urban Trees and Vegetated Roofs

This section examines the different benefits which both urban trees and vegetated roofs can provide to the urban environment in order to determine the ability of vegetated roofs to offset the loss of the urban tree canopy within Atlanta. Through a review of the literature, different economic, environmental, and social benefits examine specific ecosystem services of trees and vegetated roofs. While the term ecosystem services has been previously defined and discussed, it is important to keep the overall umbrella of benefits in mind while reading specific journals and case studies in order to better understand how different methods of green infrastructure can positively benefit their surroundings. By providing provisioning, regulating, and cultural services to urban areas, both trees and vegetated roofs help to combat negative environmental effects of urbanization.

Before the thesis gets into specific examples of benefits provided by trees and vegetated roofs, three table serve as "roadmaps" to highlight specific examples found throughout the literature review. Highlighted are specific benefits of trees (Table 1) and vegetated roofs (Table 2), along with references so that the reader can quickly access specific benefits if desired. All references in the tables are the same throughout the thesis and are found at the end of the document in the references section. Studies with direct benefit comparisons between trees and vegetated roofs (Table 3) are also provided for reference.

Table 1: Literature review matrix of benefits of trees

Authors	Tree Benefits									
	Economic					Environmental				Social
	Home Values	Energy Savings	Air Pollution Savings	Stormwater Savings	Overall Economic Value	Transpiration / UHI	Solar Radiation / UHI	Air Pollutant Removal	Stormwater Retention	Social Benefits
Anderson and Cordell 1988	x									
Bell et al. 2005										x
Bordelon n.d.			x					x	x	
Bradshaw, Hunt, and Walmsley 1995					x					
Cardelino and Chameides 1990								x		
Chomitz 2007									x	
Laurie 1979							x			
Lull 1971									x	
Monty 2003			x	x						
Nowak 2006			x					x		
Nowak 2017		x				x		x	x	
Nowak and Crane 2002			x					x		
Nowak and Dwyer 2007							x	x		x
Nowak et al. 2014			x		x			x		
Nowak, Crane, and Stevens 2006			x					x		
Nowak, Hirabayashi, et al. 2013			x					x		
Orlandini et al. 2017										x
Purdue University 2002							x			
Sicard et al. 2018								x		
Tyrväinin et al. 2005							x		x	
U.S. Geological Survey n.d.						x				
van den Bosch 2017										x

Table 2: Literature review matrix of benefits of vegetated roofs

Authors	Vegetated Roof Benefits														
	Economic						Environmental						Social		
	UHI / Air Pollution Savings	Stormwater Savings	Energy Savings	Longevity of Building Rooftop	Productivity in the Workplace	Real Estate Value / Rent Prices	UHI	Air Pollution Removal	Stormwater Retention	Energy Reductions	Acoustic Reductions	Habitat Restoration	Worker Happiness	Health and Stress Benefits	Creation of Jobs
Bass et al. 2003							x								
Baumann and Kasten 2010												x			
Cantor and Peck 2008			x				x								
Cascone et al. 2018			x					x		x					
Center for Neighborhood Technology 2011	x		x												
Clark, Adriaens, and Talbot 2008	x														
Clements et al. 2013						x									
Connelly and Hodgson 2013											x				
Cummings et al. 2007							x								
Currie and Bass 2008								x							
Deutsch et al. 2005								x	x						
Deutsch et al. 2007		x													
Dwivedi and Mohan 2018							x								
Herrera-Gomez, Quevedo-Nolasco, and Pérez-Urrestarazu 2017							x								
Heschong and Saxena 2003					x								x	x	
Jayasooriya et al. 2017			x					x		x					
Jim and Tsang 2011							x								
Lalošević et al. 2018							x								
Lee, Kim, and Lee 2014							x								
Loiola, Mary, and Pimentel da Silva 2019									x						
Mahmoud et al. 2017			x							x					
Malina 2010			x				x								
Mirzababaie and Karrabi 2019			x							x					
Missios et al. 2005	x						x		x	x					
Moran, Hunt, and Smith 2005									x						
N. Zhang et al. 2017							x								
Norton et al. 2015							x								
Oberndorfer et al. 2007				x					x						
Palla, Gnecco, and Lanza 2010									x						
Porsche and Köhler 2003				x											
Rosenzweig et al. 2009							x								
Rowe 2011								x	x						
Saadatian et al. 2013							x								
Saiz et al. 2006							x								
Scholz-Barth and Tanner 2004							x								
Shafique and Kim 2017							x								
Speak et al. 2012								x							
Stern, Peck, and Joslin 2019								x	x	x					x
T.L. Carter and Rasmussen 2006									x						
Tim Carter and Butler 2008									x						
Timothy Carter and Jackson 2007									x						
U.S. General Services Administration 2011b	x	x	x	x		x			x						
van der Meulen 2019									x		x				
Vijayaraghavan 2016											x				
Weiler and Scholz-Barth 2009									x						
Whittinghill et al. 2014								x							
Xiao and McPherson 2002									x						
Yang, Yu, and Gong 2008								x							
Z. Zhang et al. 2019									x						

Table 3: Literature review matrix of comparisons between tree and vegetated roof benefits

Authors	Direct Comparisons of Trees with Vegetated Roofs
Coutts and Harris 2013	x
Currie and Bass 2008	x
Deutsch et al. 2007	x
Jayasooriya et al. 2017	x
Ng et al. 2012	x
Rosenzweig et al. 2006	x
Rosenzweig et al. 2009	x
Sicard et al. 2018	x
Yang, Yu, and Gong 2008	x

Human history with trees began with their use for survival in the form of fruit and other food cultivation, followed by use for wood, fuel, timber, shelter, and finally for aesthetics and environmental purposes. While their use within the history of culture and society has evolved, their benefits to both the environment and humans have not. Viewed by most mainly for their aesthetic qualities, trees provide a myriad of benefits to the urban environment.

Atlanta had a large reduction in the percentage of tree cover during the latter half of the 1900s, yet the city still remains one of the most heavily forested in the United States. A study by Georgia Tech found that Atlanta had the most tree cover of cities surveyed at 47.9%, with Charlotte second at 45% (Giarrusso and Smith 2014). This high percentage is due to the natural setting of the city within the Piedmont ecoregion, as well as the climate and recent tree preservation ordinances. Atlantans are lucky to live in a city so heavily populated by trees, not just for the aesthetic quality they bring, but also for other benefits and ecosystem services provided by urban trees.

Apart from simply looking nice, trees play an important role in economics, the environment, and social lives. From an economic standpoint, trees are relatively inexpensive to install, can provide added real estate value to a property, and can help reduce energy costs for buildings when placed correctly on a site. Environmental benefits of trees include the uptake and removal of harmful air pollutants, the sequestration of carbon, CO_2 absorption and the release of oxygen, water storage and stormwater management, the reduction of the urban heat island, and the softening of UV radiation. From a social standpoint, trees provide shade in the summers, provide food, help reduce local noise, provide recreation, and can be a relief from mental stress. These are just a few of the benefits which urban trees provide. As the list is long, the following sections detail some of these benefits noted in studies and papers to provide a better understanding of how Atlanta's urban trees benefit the city.

Economic Benefits of Urban Trees

Trees provide multiple economic benefits to urban environments. Aside from being relatively inexpensive to plant and maintain throughout their life, they can raise property values, bring about building energy cost reductions, and provide savings due to pollution removal and stormwater management. In the United Kingdom, the value of urban trees was estimated at 200 billion pounds sterling (GBP) (~$246 billion USD) in 1995 (Bradshaw, Hunt, and Walmsley 1995). In a 1980s survey, it was found that single-family home sales in Athens, GA were between 3.5% and 4.5% higher due to the presence of landscaping and trees (Anderson and Cordell 1988). When placed correctly, trees are able to effectively shade buildings in order to decrease their energy use in the summer. In some climates they are also effective at blocking the wind during the winters, which also provides energy savings. Studies have shown that through proper placement, trees are able to provide energy savings of 38.8 million megawatt hours per year, which averages to around a 7% reduction in building energy use (Nowak 2017).

In terms of economic value due to air pollution removal, trees offer many savings. A tree is able to produce over $30,000 USD in oxygen, remove $62,000 USD of air pollution, and recycle more than $37,000 USD worth of water over a fifty-year lifespan (Bordelon n.d.)**.** Urban trees in Washington, D.C. have been found to provide close to $50 million USD in annual savings due to air pollution reduction (Monty 2003). Data from 2010 shows that trees in the conterminous United States had human health effects worth $6.8 billion USD. When looking at the total economic benefit of those trees, not just in terms of human health, it is estimated that the total economic value is $86 billion USD (Nowak et al. 2014). Even though this data was taking into account all trees within the United States, not just urban areas, close to 70% of the $6.8 billion USD in value was due to urban trees. This high percentage is because of the population difference between urban and rural areas. The greater the population of a city, the greater the economic benefits will be for trees due to health benefits and cost reductions.

Environmental Benefits of Urban Trees

Aside from providing a positive economic value, trees also play an important environmental role within urban settings. Due to climate change, air quality is expected to worsen and solar radiation will intensify, which can lead to higher concentrations of ozone in the atmosphere (Tyrväinin et al. 2005). If no measures are taken, they can have adverse effects to human and plant health. One of the strategies to combat this change is through trees. Through regulating services, trees help to lower the UHI, absorb solar radiation, help maintain healthy soils, capture stormwater, and slow water runoff. They are also able to capture and reduce pollutants (such as ozone, sulfur dioxide, and nitrogen oxides), eliminate particulates, and sequester carbon.

Urban Heat Island / Ultraviolet Radiation

Since the end of the nineteenth century, the earth has seen its average temperature rise by 0.6°C (Nowak 2006). While this may not seem like much, future predictions are a little more eye-opening. Through urbanization, pollutants, and a rising population, by 2100 the temperature is expected to rise by another 1.4-5.8°C (Nowak 2006). One way to limit this temperature rise is through green infrastructure, specifically through trees. Urban trees have the ability to affect local microclimates and possibly the global climate through their ecosystem services. Through transpiration and shade, trees are able to assist in the reduction of solar radiation as well as a reduction in the UHI.

Whether a single tree, a row of street trees, a small group of trees on an undeveloped lot, or a full forest, trees are able to assist in temperature reduction. Through the process of transpiration, trees are able to absorb and remove energy, which helps to keep their surroundings cooler than they would be without trees. Some larger oaks are able to transpire around 40,000 gallons (0.12 acre-feet) per year, or just over 100 gallons every day (U.S. Geological Survey n.d.). Not only does transpiration aid in lowering temperatures, but it can also help in reducing pollution, thus having positive effects on human health (Nowak 2017).

Another benefit of urban trees in helping to lower the UHI is through their ability to absorb solar radiation. Because urban areas can contain between 60-70% man-made surfaces and are filled with glass, they can be highly reflective. Lower temperatures are recorded by shading some of these surfaces from direct sunlight. In Munich, Germany, it was determined that through a 10% increase in the urban canopy, surface temperatures decreased by 1.4°C (Tyrväinin et al. 2005). Asphalt, concrete, brick, or bare roofs can reflect up to 50% of the radiation they receive (Laurie 1979). Trees are able to absorb and reduce this solar radiation by more than 90% (Nowak and Dwyer 2007), and then either reflect some back to space, or store the energy for use in transpiration and photosynthesis.

The urban tree canopy is also able to act as a horizontal “line of defense” for city streets. During the summer months, heat which radiates off of buildings is absorbed by the canopy and raised above the street level by trees, while during the winter the same trees are able to capture some of the heat which escapes the earth, helping to create a warmer zone at the level (Laurie 1979).

Lastly, through the absorption of solar radiation, trees are able to better protect humans from overexposure to ultraviolet (UV) rays from the sun. Trees can provide an SPF value of up to 10 (Purdue University 2002), which can limit the occurrence of skin cancers or other illness due to too much UV exposure.

Air Pollutants

Trees help create better air quality in cities through many different methods. They improve local microclimates through temperature reduction, they help to reduce building energy usage, and they help to remove air pollutants from the environment. While Atlanta may not have as many air pollution concerns as other world cities, within typical urban environments humans can be exposed to over 200 different air pollutants or classes of pollutants (Sicard et al. 2011), which is a reason why it is important to have a healthy urban tree canopy within cities. Even though urban trees and shrubs typically improve air quality by less than 2%, their role in keeping cities healthy and keeping the likes of ozone at bay is still important (Sicard et al. 2018), as it is recognized as the most damaging pollutant to plants (Rich 1971).

When Atlanta went through a period of accelerated urbanization in the 1970s and 1980s, close to 20% of the existing forest was lost. A 1990 study into the effects of urbanization and ozone found that a 20% reduction in the Atlanta forest would increase ozone concentrations by 14%. This increase would be due to the rise in temperatures caused by the loss of forests (Cardelino and Chameides 1990).

Tree pollution removal rates depend on multiple factors, such as the amount of tree cover, the concentration of pollutants, the climate and growing season, and the percentage of evergreen trees within an area (Nowak et al. 2014). These all combine to bring about the greatest amount of pollution removal for an urban area. In 1994, a study of pollutant removal by urban trees in 55 United States cities showed the removal of over 711,000 metric tons of pollution for a monetary value of $3.8 billion USD (Nowak, Crane, and Stevens 2006). Atlanta was one of the cities in the study and findings showed that the city's trees removed a total of 514 metric tons of O_3, 423 metric tons of PM_{10}, 135 metric tons of NO_2, 93 metric tons of SO_2, and 35 metric tons of CO for a total of 1,200 metric tons of total pollution removal. This equates to a monetary value of almost $6.5 million USD in savings that for Atlanta had for the year (Nowak, Crane, and Stevens 2006). Even with these numbers, the study found the air quality was only minimally improved, with just a 0.7% improvement recorded in ozone, PM_{10}, and SO_2 air quality. NO_2 was improved by 0.5% and CO by only 0.002% (Nowak, Crane, and Stevens 2006).

A 2006 study using computer simulations with pollution data from 2000 estimated that Atlanta's trees are able to remove 672 metric tons of O_3, 528 metric tons of PM_{10}, 181 metric tons of NO_2, 89 metric tons of SO_2, and 39 metric tons of CO for a total of 1,508 metric tons of pollution removal. This accounts for 12 grams of pollution removal per square meter of canopy coverage, higher than the 9.3 average for all cities modeled, and added up to a total monetary value of over $8.3 million USD for the city (Nowak 2006). The change in results from 1994 to 2000 helps to highlight the benefits of Atlanta's tree protection strategies and replanting efforts in the late 1990s.

In 2010, trees within the conterminous United States removed 17.4 million tons of air pollution at a monetary value of over $6.8 billion USD (Nowak et al. 2014). Within that number, urban trees removed over 650,000 metric tons, with the remaining amount removed by trees in rural areas. Georgia was actually the third highest remover of pollutants behind California and Texas, with the state seeing over 731,000 tons of air pollution removed at a monetary value of $352 million USD (Nowak et al. 2014). The majority of pollution removed was in rural areas, however the monetary value due to removal in urban areas was more than double that of rural areas because of the benefits to human health and the greater populations in urban areas.

One of the most harmful pollutants to human health is $PM_{2.5}$. Due to its size, it has a greater chance to get to the human respiratory system and bloodstream which can cause a myriad of health issues, including cancer and premature death. Nowak, Hirabayashi, et al. (2013) studied the effects of trees on $PM_{2.5}$ in ten cities within the United States, including Atlanta. Results estimated that Atlanta's trees are able to remove 64.5 tons of $PM_{2.5}$ at a monetary value of over $9 million USD annually (Nowak, Hirabayashi, et al. 2013). While the amount of $PM_{2.5}$ removed is far less than that of PM_{10}, the monetary value associated is greater due to the health risks of $PM_{2.5}$. The removed $PM_{2.5}$ by Atlanta's trees was the highest of all cities studied, but still only represented a .24% improvement to the air quality (Nowak, Hirabayashi, et al. 2013).

One of the greatest benefits of trees is their role within the carbon cycle. Models show that within the United States, urban trees are able to store 643 million tons of carbon and can sequester 25.6 million tons of carbon (Nowak 2017). The main difference between these two methods of carbon interaction is that storage refers to the holding capacity of a tree, whereas sequestration is the long-term storage and ultimate removal of CO_2 from the atmosphere. A tree can reach its full potential of carbon storage at around ten years old, when it has the ability to store almost 50 pounds of CO_2 per year (Bordelon n.d.).

Trees are able to store far more carbon than they are able to sequester, however the 643 million tons they can store is equal to the amount emitted by the United States in just 5.5 months (Nowak 2006). Per person, it takes an average of 1,025 trees to offset an individual carbon footprint (Saving Nature 2019). That number could be lower and there are estimates that if every family in the United States planted a tree, atmospheric CO_2 could be reduced by a billion pounds each year (Bordelon n.d.). In terms of monetary value, carbon storage of urban trees within the conterminous United States is a $50.5 billion USD value and carbon sequestration carries a $2 billion USD value per year (Nowak and Crane 2002).

Forests are able to fix, on average, one ton of carbon per acre per year. In 2017, the United States emitted 5.42 billion tons of CO_2 (Ritchie and Roser n.d.). While the past 30 years have seen the United States start to get CO_2 somewhat under control, this would still require almost 8.4 million square miles of forest in order to fix the emission rate. For perspective, 8.4 million square miles is roughly the size of the United States, Canada, and Mexico combined. Large trees are able to store up to 1,000 times more carbon than smaller trees and can sequester over 90 kilograms (kg) of carbon per year compared to just one kilogram of carbon for small trees (Nowak and Dwyer 2007).

Within Atlanta, a 2002 estimate of carbon storage and sequestration rates of city trees found that the urban canopy had the potential to store over 1.2 million tons of carbon and could sequester 42,100 tons of carbon per year. Estimates were also calculated for each state's ability to store and sequester carbon in a 2013 study, where it was found that Georgia trees were capable of storing 38.5 million tons of carbon and could sequester over 1.7 million tons of carbon per year (Nowak and Crane 2002). In both of these categories, Georgia ranked third amongst all states, behind Florida and Texas.

From 2005-2009, Atlanta lost 1.8% of its tree cover. Nationally, the United States is losing close to 19,500 acres of tree cover to urban areas per year (Nowak and Greenfield 2012). The national trend is seeing tree cover reductions with impervious surfaces on the rise. Even though there is potential for additional trees within urban areas, mindsets and development patterns need to change in order to create a positive impact to cities. If continued on the current path, cities will have less ability to store and sequester carbon within urban areas.

On the other side of the carbon cycle are trees' abilities to provide oxygen. Within the United States, forests produce around 67 million tons or oxygen per year, which can cover the annual consumption of two-thirds of the population and is over 85 times greater than the amount of air pollution removed per year (Nowak, Hoehn, and Crane 2007). In 2007, oxygen statistics for 16 cities in the United States and Canada were compared using 0.1-acre circular plots. Of these cities, Atlanta was studied using data from 1997 and 205 different plots. Findings showed Atlanta's trees were able to produce 94,800 tons of oxygen per year, which was the highest amongst all cities studied. This production rate offsets 67% of the city's population, the second highest of the cities studied. It was found that every acre of coverage could supply nine people with their yearly supply of oxygen (Nowak, Hoehn, and Crane 2007).

Even with the large amount of oxygen that trees are able to produce, the comparative services which they provide in terms of air pollution removal or carbon sequestration are still greater. From a monetary standpoint, trees' value of oxygen production is very small compared to values associated with air pollution removal. This is partly due to the fact that so much oxygen exists already within the atmosphere and is produced as well through water systems. There is approximately 700 times more oxygen in the atmosphere than carbon dioxide (Nowak, Hoehn, and Crane 2007), so the ability for trees to store and sequester carbon, as well as remove pollutants, is far more valuable than their production of oxygen.

Overall, trees have a major impact on urban environments in terms of pollution removal and oxygen production. Even with these benefits and the amount of air pollutants removed, trees only reduce the concentration of pollutants by less than 1% (Nowak et al. 2014). Yet with just that small percentage improvement, the United States is able to save billions annually in health costs along with other benefits. By adopting further planting guidelines, policies, and/or other green infrastructure methods, a further impact could be made to urban environments, human health, and economic savings.

Stormwater / Water Runoff

Within urban areas, the number of man-made surfaces and impervious materials are much higher than rural areas. Therefore, water has less opportunity to infiltrate the earth's surface and complete the hydrologic cycle. When planning cities, water is designed to leave spaces as quickly as possible, directing the water flow to drains where it moves through sewer systems and eventually discharges into rivers, lakes, and other bodies of water. Urbanization increases both the flow intensity and quantity during rain events, while decreasing the amount of evapotranspiration which would normally be allowed to take place with the presence of more trees.

Stormwater runoff in cities is one of the leading causes of water pollution. Because urban areas contain more pollutants, runoff carries these into sewer systems and ultimately into streams, rivers, and lakes. Runoff also has the potential to accelerate stream flows and damage aquatic habitats (Nowak 2006). One study examined the effects of a 10% loss in forest within a 3,853 square kilometer (1,487 square mile) watershed in northern Thailand and found that runoff increased by 6% in the wet season and 16% in the dry season (Chomitz 2007). Due to the lack of forest cover, soils remain wetter as there are no "sponges" to remove excess water, and soils become compacted due to deforestation, which affects their ability to absorb rainfall. The same study in northern Thailand found another negative aspect of deforestation to be the flow rates of local rivers. In one case, the river experienced increased flow rates of over 25%, affecting over 100 million people (Chomitz 2007).

Within urban areas, trees are able to assist in calming the rate of runoff by temporarily capturing rainfall and gradually releasing it, lessening stress on sewers, reducing flooding, and improving water quality. Another service which trees provide in calming runoff is through transpiration. Tree roots capture water and around 99% of that water is transpired back into the atmosphere through their leaves (Lull 1971). They also manage stormwater by intercepting precipitation before it hits the ground, increasing the holding capacity of soils, and reducing the impact velocity of rain which aids in stopping erosion of soils (Tyrväinin et al. 2005). Findings show that 100,000 gallons (0.30 acre-feet) of rain can be intercepted by 100 mature trees and that just a 5% increase in canopy coverage could reduce runoff by 2% (Bordelon n.d.).

In Washington, D.C., trees in the city provide over $4.7 billion USD in stormwater benefits annually (Monty 2003). Planting more trees helps take strain off of sewer systems by promoting infiltration of rainwater, recharging groundwater, and improving the health of soils. This is important as soils are able to store more stormwater than trees themselves, as well as filter pollutants and delay runoff (Kuehler, Hathaway, and Tirpak 2017). By reducing the risk of flooding, trees help to prevent pollutants, chemicals, and harmful pathogens from entering bodies of water (Nowak 2017). Not only do all of these factors help the environment, but human health benefits can also occur through the stormwater management by urban trees.

Social Benefits of Urban Trees

Trees can play a vital role within the social, mental, and physical well-being of urban areas. They can reduce stress, provide recreation and comfort, provide aesthetics within the landscape, provide food production, and can reduce noise when placed strategically. Urban trees can improve human health by reducing stress and can also provide character to a city (Nowak and Dwyer 2007). In some instances, they are able to provide community connections. In Chicago, Illinois, it was found that some inner-city areas which contained urban trees brought about stronger neighborhood ties, saw more use of common spaces, fewer crimes, and provided a greater sense of safety (Nowak and Dwyer 2007).

During hot days, people tend to seek shade when out in open areas, parks, or walking down the streets. The cooling effect from urban trees can provide more comfort for people on hot days, while the same trees can protect the urban population from strong or cold winds during the winter (Orlandini et al. 2017). When placed intentionally throughout the landscape, trees can create or enhance vistas, or can create a sense of place, or scale, when placed within the large urban forms of cities (Bell et al. 2005).

Lastly, due to the stresses that typically come with living in urban environments, mental issues are typically more common for the population when compared to those living in rural areas. Trees can help to restore a connection with nature and alleviate stress or other mental illness by providing an escape for urban citizens (van den Bosch 2017). Whether planning a new city, developing a small property in the middle of an urban area, or planting a singular tree on a lot, trees should not be regarded just in terms of their economic or environmental benefits, but also the social benefits that they can bring to urban areas.

Arguments Against Urban Trees

Even with the many the benefits of urban trees, there are still some arguments against their planting. While they provide shade in the summer, helping to cool the ground or adjacent buildings, they can also cast shade in winter, especially if they are evergreen. This makes the ground even cooler and potentially dangerous if the area is prone to freezing temperatures with ice forming on the ground. Trees can also disrupt traffic, cause unwanted cracks and breaks in the pavement or concrete sidewalks, their roots can damage pipes, and leaf litter can clog drains (Lawrence 2006). Another argument against urban trees is the amount of debris that they can create, with deciduous trees shedding leaves every winter and branches breaking off during storms or in old age. People could also argue against trees in terms of safety and security issues, with some blocking cameras or views especially during the night. This thesis has highlighted many of the economic and health benefits of trees, but the other side of these arguments are the costs associated with planting, maintaining and potentially removing trees, the potential for trees to add to a building's energy costs if not correctly placed on a site, and the health risks and allergies due to the emission of pollen (Lyytimäki 2017) . Lastly, trees emit VOCs as part of their natural processes, but not enough to adversely affect the environment. That, along with carbon emitted when trees die and decompose, can be seen as environmental arguments against trees. Even with these arguments, their benefits in the removal of pollutants outweigh their emission throughout their lifetimes.

Vegetated Roof Benefits

When it comes to the benefits of vegetated roofs, they share many of the same ecosystem services as urban trees. When some of the earliest rooftops in Scandinavia were vegetated, they were done so as a means for thermal comfort. They kept the cold out during the winters while providing a cooler dwelling in the summer heat. One of the greatest benefits of vegetated roofs today is related to those earliest uses. They are able to better insulate the buildings they adorn and help reduce energy costs. Other early uses of vegetation upon rooftops and terraces was from a social standpoint, providing an oasis in the sky or a planted terrace to be immersed within. While not constructed as much for this purpose anymore, they still provide added greenspace to cities, can be destinations for workers on lunch breaks, or can provide a pleasing sight to anyone living or working above them.

Unlike with urban trees, plenty of spaces within cities are available for the use of vegetated roofs as green infrastructure. In some areas of New York City, over 90% of the ground area is impervious (Rosenzweig et al. 2009) and cannot accommodate street trees. In many cities, rooftops can account for upwards of 40-50% of impervious areas and can be fitted with either permanent or modular vegetated roof systems. One study estimated the total quantity of rooftops within the world's urban areas by assuming an average 25% coverage of rooftops within those areas. When this formula was followed, it was estimated that the total area of urban rooftops is close to 380 billion m^2 (Akbari, Menon, and Rosenfeld 2009). This equates to over 146,000 square miles of total urban rooftops in the world, which is just smaller than the country of Norway, the 62nd largest country in the world. Many areas have begun to regulate vegetated roofs on developments, helping to change the landscape of urban settings. For example, Germany had planted almost 90 square kilometers of vegetated roofs by 2014, the most of any country in Europe (Cascone et al. 2018).

Vegetated roof development has arisen in different areas of the world due to different cultural patterns and ways of thinking. As mentioned above, Germany is a world leader in developing vegetated roofs. This comes due to environmental concerns and mitigating the loss of the natural landscapes because of developments. In some areas of Scandinavia, vegetated roofs are developed due to a feeling of national heritage and being close to nature, whereas North American roofs are developed more for economic gains, focusing on the long-term savings they can bring to buildings and urban areas (Dunnett and Kingsbury 2008).

While Atlanta does have some vegetated roofs within its city limits, the city is still nowhere close to many of its domestic counterparts such as Washington, D.C., Chicago, New York City, or Portland. The development of vegetated roofs in the United States, and especially in the Southeast, is still very young. This is attributed mainly to higher initial costs and an overall lack of awareness in terms of design, development, and benefits (Tabatabaee et al. 2019).

In a later section, this thesis will examine some case studies at the international and domestic levels, as well as look at some existing vegetated rooftops within the city of Atlanta. This section will focus on the ecosystem services which vegetated roofs can provide for urban environments in terms of economic, environmental, and social benefits, similar to the previous section on trees. From an economic perspective, vegetated roofs generally contribute to building energy savings, increase property value, increase the lifespan of roofs, and result in a positive life-cycle cost. The environmental benefits include removing air pollutants, stormwater retention and the ability to reduce flooding, mitigation of the UHI, noise reduction, and the ability to increase biodiversity. Lastly, from a social standpoint, vegetated roofs add greenspace to urban areas where impervious surfaces dominate the landscape, they can be pleasing to look at when viewed from above, they can help to relieve stress, they have the ability to support urban agriculture, and they provide space for recreation. While these are some of the scientific benefits of vegetated roofs, everyone has different ideas about what is important when it comes to their development. Tabatabaee et al. (2019) conducted interviews and questionnaires with 28 experts in the vegetated roof industry. The experts were architects, engineers, contractors, and designers and they ranked their opinions on the benefits, opportunities, costs, and risks of vegetated roofs. The top benefits were energy savings, energy efficiency, stormwater retention, property value increases, and overall aesthetics. The top opportunities of vegetated roofs were reduced urban flooding, the awarding of a green building certificate, increased roof life, a self-resilient urban society, and the mitigation of UHI (Tabatabaee et al. 2019). The findings show that everyone can have different perceived benefits when it comes to vegetated roofs and that education on their individual benefits is important for their development and success in urban areas.

Economic Benefits of Vegetated Roofs

One of the main arguments against the development of vegetated roofs is their high initial construction costs. Even so, vegetated roofs are able to provide many economic benefits, which pay out in the long run. Once thought of as strictly an amenity for buildings (Moran, Hunt, and Smith 2005), knowledge dissemination is helping vegetated roofs become a viable money-saving option for developers. Aside from the cost reductions in terms of air pollutant removal and stormwater management that vegetated roofs provide, they can contribute to a building's energy savings in summer and winter, can prolong the life of the building's roof, and can positively affect the building's property values.

Although difficult to put a hard number on UHI savings at a building level, it is estimated that vegetated roofs are able to save around $0.23 USD/SF of coverage per year, due to solar reflectivity, energy reduction, and temperature mitigation. In terms of air pollution, nitrogen-oxide savings is between $0.0008 and $0.59 USD/SF/year, depending on vegetation used (U.S. General Services Administration 2011b). One calculation for a 5,000 SF roof showed savings from NO_2 removal to be just over $100.00 USD/year, while savings from SO_2 removal for the same sized roof is $35.20 USD/year (Center for Neighborhood Technology 2011). Other studies have attempted to quantify the amount of environmental savings vegetated roofs can bring, with one study examining a 2,000 m^2 (21,527 SF) roof and finding that health benefit savings ranged between $890-$3,390 USD/year (Clark, Adriaens, and Talbot 2008).

One of the biggest economic bonuses for vegetated roofs is their impact on stormwater. While all vegetated roofs can provide stormwater savings, proportionally speaking larger roofs are able to accrue greater savings. In many cities, combined sewer overflows (CSO) are a problem with heavy rainfall events. A CSO occurs during these times because the sewer system is transporting runoff, sewage and wastewater all in one system. When excess rain occurs and runoff is high, the volume of water is too much for the system to handle; it either overflows into the city or bypasses the treatment plants and empties directly into water systems. In Washington, D.C., the cost to treat stormwater is around $615.00 USD per million gallons. Multiple scenarios have been studied using trees, tree boxes, and vegetated roofs within the city in order to alleviate stormwater costs. In a study by Casey Trees, it findings showed that through installing 11 million SF of vegetated roofs, CSO would be reduced by 95 million gallons (291-acre-feet). If 55 million SF of vegetated roofs were installed, that number would increase to 435 million gallons (1,334-acre-feet), or a 19% reduction. Taking these figures into account, stormwater treatment would be reduced by $1.4-$5.1 USD million, respectively (Deutsch et al. 2007).

In terms of energy use, vegetated roofs provide an average savings of $0.166 USD/SF nationally (U.S. General Services Administration 2011b). While this might not be a large amount on an individual square foot basis, for a 5,000 SF roof it equates to $830.00 USD/year. While vegetated roofs can provide energy savings for every building they adorn, the savings are greater on shorter buildings due to the amount of energy required for high-rises.

Vegetated roofs are able to extend the lives of rooftops. When a standard black roof is installed on the top of a building, the waterproofing membrane can be harmed by UV light and can subsequently crack due to fluctuating temperatures, causing them to become brittle (Oberndorfer et al. 2007). Through the use of vegetation, the roof's lifespan can be extended due to the added protection of the roof membrane. One study estimated that a conventional rooftop would last an average of 17 years, while a vegetated rooftop could last up to 40 years (U.S. General Services Administration 2011b). Some researchers think this number could be even higher, and in Berlin, Germany, some vegetated rooftops are over 90 years old, which is thought to be the typical lifespan for those roofs (Porsche and Köhler 2003). In Zurich, Switzerland, a water treatment facility was topped with a vegetated roof in 1914 and lasted 91 years before it was repaired for the first time in 2005 (Rowe 2011).

A cost/benefit analysis was performed for national averages in the United States of three sizes of green roofs: 5,000, 10,000, and 50,000 SF. The roofs were assumed to have a 3-6" substrate and analyses were performed assuming a 50-year period. For the 5,000 SF roof, the initial premium was $12.60 USD/SF and the net present value (NPV) of installation, replacement and maintenance for the 50-year period was $18.20 USD/SF of vegetation. When it comes to savings from the 5,000 SF roof, $14.10 USD of stormwater fees and improvements are avoided per square foot and energy has a $6.60 USD NPV. This is equal to $20.70 USD worth of savings against the initial NPV of installation, replacement and maintenance of $18.20 USD, so the roof sees a total NPV of $2.50 USD/SF/year. This positive number means the roof has an initial cost recovery of roughly 6.4 years with a return on investment of 220%. Larger vegetated roofs have cheaper square foot installation costs and are able to see larger savings due to benefits, so the 10,000 and 50,000 SF roofs see a shorter initial cost recovery and larger rate of return. (U.S. General Services Administration 2011b)

Also calculated through the study were the economic benefits of carbon emission, sequestration and absorption, as well as real estate value and community benefits. The savings for these for the 5,000 SF roof were $2.10 USD, $120.10 USD and $30.40 USD/SF of coverage, respectively (U.S. General Services Administration 2011b).

Another study looked into the economic value of a 5,000 SF vegetated roof and divided savings in multiple categories. They found that stormwater benefits from the roof totaled $6.53 USD, energy savings would be $552.35 USD, air quality improvements provided $100.83 USD in savings, and CO_2 reduction totaled $49.04 USD in savings. Altogether, this 5,000 SF roof would account for $708.75 in annual benefits (Center for Neighborhood Technology 2011). The study took this research a step further and scaled-up the benefits for a chosen area of Chicago. They assumed a 1,200,000 SF coverage of new green roofs in the city, all at 5,000 SF each. This equated to 240 rooftops, which when multiplied by the total savings calculated above would see a value of over $170,000 USD/year for the vegetated roofs (Center for Neighborhood Technology 2011).

Every roof does not provide the same amount of savings and benefits. This is due to variations in orientation, local climate, height above street-level, roof type, and maintenance. A study from Catania, Italy simulated the benefits of a 270 m^2 (2,906 SF) vegetated roof on a seven-story building. They simulated both a sedum covered roof and a salvia covered roof and found average temperatures were reduced by over 20%, energy consumption was reduced by upwards of 23%, and initial investment recovery for the roofs was between 13.4 years and 17.9 years. (Cascone et al. 2018)

While vegetated roofs provide many benefits to the environment outside of the building, there are also associated cost savings within the building. Studies have found that when workers have a view of vegetation from their office, they are more productive (Heschong and Saxena 2003) and are absent less frequently due to health and stress benefits. Analysis shows that vegetated roofs are able to increase real estate value by around $13.00 USD/SF of coverage (U.S. General Services Administration 2011b). It has also been found that buildings with vegetated roofs are able to charge higher rents than buildings without vegetation on the rooftops (Clements et al. 2013). Within Washington, D.C., if vegetated roofs replaced all conventional roofs (5.9 million SF), the 50-year NPV would be $22.7 million USD. The total benefits for the community if this were to happen would be almost $180 million USD (U.S. General Services Administration 2011b).

Many more studies have performed further in-depth investigations into the complete financial benefits of vegetated roofs which this thesis will not look further into. It is the goal of this thesis, as well as this section, to help the reader realize some of the economic benefits that vegetated roofs can bring to a development and an urban area in order to better start the conversation of their inclusion in city policy or individual developments.

Environmental Benefits of Vegetated Roofs

Different areas of the world view vegetated roofs in different ways. The United States sees the inclusion of vegetation on rooftops mainly in terms of economics, whereas many cities in Europe view vegetated roofs from an environmental perspective. This has led them to become mandatory on new construction in many European cities, even without many incentives to reduce costs (Cantor and Peck 2008). While inclusion without incentives is somewhat rare, it goes to show how serious some areas of the world are about green infrastructure, especially vegetated roofs, and their commitment to environmental changes within their urban areas.

In Toronto, Canada, an initial investment for two vegetated roofs in 2000 lead to estimates that if only six percent of the total rooftops were converted to vegetated roofs, temperatures could be reduced by as much as 3.6°F, greenhouse gas emissions could be greatly decreased, and $1 million CAD in energy costs could be saved (Malina 2010). In addition to these cost benefits, the city would also see a reduction in its annual smog advisories. Another study into the effects of vegetated roofs in Toronto in 2005 assumed 100% coverage on all roofs over 350 m^2 (3,767 SF). Conclusions stated that if this was a reality, the city would see its UHI effect reduced by 25%, and drastic reductions in stormwater runoff, energy use, and CSO events. Overall, the city would see initial cost savings of just over $313 million CAD (Missios et al. 2005).

Due to these initial studies and further implementation of policy surrounding vegetated roofs in Toronto, the city saw the development of 5.4 million SF of vegetated roofs from 2009-2018. This development led to the annual retention of 58 million gallons (178 acre-feet) of stormwater, 225 tons of sequestered carbon, 3.2 million kWh of energy savings, 1.6 million kWh of energy savings on surrounding buildings without vegetated roofs, and the significant creation of jobs in the construction industry (Stern, Peck, and Joslin 2019).

While this is just one example of some measured environmental benefits resulting from the inclusion of vegetated roofs within city policy and urban environments, there are many more examples of simulations, estimates, and built work examined in the remainder of this section.

Urban Heat Island / Ultraviolet Radiation

Within urban areas, most often roofs can be the hottest surfaces. This is due to their makeup, solar absorption, as well as the fact that they are usually the highest points in cities, above the tree canopy and without shade. With increased global temperatures, more instances of extreme heat events (EHE) throughout urban areas can be expected. These events can cause higher rates of mortality, but can be lowered with the inclusion of more green infrastructure practices, such as vegetated roofs (Norton et al. 2015). While vegetated roofs may not be able to highly affect temperatures at ground-level, they can still play a key role in overall urban temperature mitigation at the rooftop level. The best use for vegetated roofs in contributing to the reduction of UHI is on large buildings, low buildings, or in areas of a city where there is limited green space at ground-level (Norton et al. 2015).

Vegetated roofs help control the UHI by reflecting solar radiation, limiting its retention and transmission through the roof (Jim and Tsang 2011), and transpiring water back into the atmosphere. Through these processes, they are able to ease the intensity of the UHI at the rooftop level, as well as allow for surfaces to cool off faster since they do not hold as much heat as bare rooftops. Substrates of only 10 cm (3.9 in) have been found to reduce the amount of heat which can penetrate rooftops (Jim and Tsang 2011). Compared to bare roofs, vegetated roofs can be anywhere from 30-60°C cooler during the day (Saadatian et al. 2013), and can act as an insulator for buildings in the winter, blocking heat from escaping through the roof.

Multiple studies have examined the benefits of vegetated roofs in mitigating UHI from all over the world. In Madrid, Spain, a simulation modeled on an eight-story residential building with a footprint of 677 m^2 (7,287 SF) found that with a vegetated roof, total environmental impacts were reduced by 1-5.3%, while the cooling load of the building was reduced by 6%. While this number was an average for the entire building, the vegetated roof was able to directly affect the cooling load of the top four floors, at a rate of 25%, 9%, 2%, and 1%, respectively (Saiz et al. 2006). The study concluded that if 50% of buildings in Madrid had vegetated roofs, when temperatures climbed above 23°C the cooling loads of the buildings would be reduced by 33%, greatly helping in the mitigation of UHI.

Another study out of Spain examined the effects of climate change and the amount of roof coverage needed for different temperature variations. In the study, three simulations were run over an area of roughly 4,500 acres. These three simulations imagined temperature increases from 1.5- 6.5°C, which is the expected rise in the city's temperature by 2100. The goal of the study was to find out how many vegetated roofs would be needed in order to combat climate change. Findings showed that for the most ideal scenario, with a 1.5°C change, 11.3% of the study area would have to be converted to vegetated roofs, consisting of just over 500 acres. When the temperature was forecasted to rise by 6.5°C, the number of vegetated roofs needed increased to 37.4%, or 1,685 acres of vegetated rooftops (Herrera-Gomez, Quevedo-Nolasco, and Pérez-Urrestarazu 2017).

An in-depth study in the Serbian capital of Belgrade selected four study locations, all with different heights, structure types, and percentage cover of green and asphalt surfaces. Temperature models were run at the pedestrian and rooftop levels at three different times of the day and once at night. This study used the ENVI-met software and found that through the use of vegetated roofs, temperatures could be reduced at the pedestrian level by up to 0.47°C with extensive roofs and 1.51°C with intensive roofs. At the roof level, temperatures decreased by up to 0.53°C with extensive roofs and 1.45°C with intensive roofs. The study also found that if vegetated roofs were combined with cool paving materials, the temperature reductions were even greater (Lalošević et al. 2018).

Another study conducted utilized the ENVI-met software in the Dadar Parsi Colony in Mumbai, India. This area is roughly 440 acres and the model assumed vegetated roof coverage percentages of 25%, 50%, and 75%. It was found that with a 50% coverage, ambient air temperature dropped by 10%, with an average reduction of 2.1°C and a maximum reduction of 3°C. A 25% coverage would see a decrease in ambient air temperature of 6%, and if 75% coverage was achieved, ambient air temperature could decrease by as much as 20% for the area (Dwivedi and Mohan 2018).

In the Yangtze River Delta of China, models assumed 25%, 50%, 75%, and 100% coverage of vegetated roofs within the area over a one-and-a-half-month-long heatwave. Conclusions stated that through the experiment, the average temperature decreases were 1.6, 2.4, 3.0, and 3.8°C for the 25%, 50%, 75%, and 100% coverage models, respectively. The maximum decrease of temperatures for those four models were 3.5, 5.4, 7.0, and 9.4°C, respectively (N. Zhang et al. 2017).

In Seoul, South Korea, a local middle school constructed a green blue roof in order to test its capabilities in mitigating UHI. A green blue roof is similar to other vegetated roofs; however, it has an added layer in its substrate in order to store more rainwater which helps to eliminate the occurrence of flash flooding and can be used for irrigation of the roof. Through monitoring, the team found that the surface temperature of the green blue roof was between 5-9°C cooler than adjacent bare roofs (Shafique and Kim 2017).

In Toronto, Canada, an ENVI-met study of three sites attempted to determine the benefits of vegetated roofs on the UHI. One site was industrial, one residential, and one mixed-use. The models found that while vegetated roofs helped to lower ambient air temperatures in all three locations, the industrial site saw the largest benefits from the roofs due to the amount of preexisting impervious surfaces and the lack of existing vegetation on-site (Bass et al. 2003).

Also, in Toronto, measurements were taken atop City Hall on their vegetated roof and compared to a neighboring black tar roof. Data collected in 30-minute intervals in August 2001 found that the vegetated roof was significantly cooler than the black tar roof. Ambient air temperature was 107°F over the vegetated roof, while the air over the black tar roof was 114°F. The surfaces of the measured roofs showed an even bigger difference, with the City Hall roof measuring between 91-119°F and the black tar roof measuring 169°F, an average difference of 64°F (Scholz-Barth and Tanner 2004).

In Florida, the University of Central Florida constructed and tested a vegetated roof on one of the campus buildings in order to determine temperature differences between it and a conventional roof. They monitored the roofs during 2005 and 2006 and found that the average temperature for the conventional roof was 90.4°F while the vegetated roof averaged 83.5°F. The maximum daily temperature for the conventional roof was 133.6°F and the vegetated roof saw a maximum temperature of 85.8°F. They also found that from 2005 to 2006, the average temperature of the conventional roof increased due to darkening of the materials, while the vegetated roof saw a decrease in the average temperature due to plant growth and establishment (Cummings et al. 2007).

In New York City, a study looked at converting all available rooftops to vegetated roofs and ran models to find out temperature data. The findings estimated a reduction of around 0.4°F for the entire city, while the largest drop in temperatures would occur at three in the afternoon and would be 0.8°F of a reduction. The team also looked in-depth at six areas of the city to find more precise neighborhood moderations of temperatures. They found that through these six areas, there was an average reduction of 1.1°F, with a maximum reduction at three in the afternoon ranging between 0.8-1.8°F (Rosenzweig et al. 2009)

While many more studies and simulation models exist on the mitigation abilities of vegetated roofs on UHI, those noted above were selected from different parts of the world and from different climates in order to illustrate that vegetated roofs can help to lower temperatures in all settings. As mentioned earlier, the more rooftops converted, the more temperatures can be affected and lowered. Recordings show that Washington, D.C. has a UHI which is an average 10.8°C warmer than its surrounding rural areas, whereas Los Angeles has a UHI between 12-17°C warmer than its rural areas (Lee, Kim, and Lee 2014). These two examples help to highlight the drastic increase in temperatures within urban areas. Any impact made on the UHI through the implementation of green infrastructure and vegetated roofs will help the future of these cities, urban areas, and global climate.

Air Pollutants

Vegetated roofs produce some of their most quantifiable benefits in the form of air pollutant removal. Their ability to clean the air depends the following few factors: the health of the plants, the position of the roof, and the conditions of air flow around the roof (Lalošević et al. 2018). It is estimated that 1 m^2 (10.76 SF) of grass on top of a vegetated roof has the ability to remove 0.1 kg of particulates per year (Rowe 2011). It is also known that cars generally produce around .01 gram (g) of particulates for every mile driven. If a car drives 10,000 miles in a year, it will produce 0.1 kg of particulates. While the removal of particulates by vegetated roofs may not seem like a large number on its own, each square meter of vegetation can be looked at as removing 10,000 miles driven per year (City of Los Angeles 2006). With that in mind, if the vegetated roof was an intensive roof with trees and shrubs, it would be able to remove even more than a simple grass roof.

An Australian study measured the impact of different green infrastructure scenarios with the i-Tree Eco software. The study site was an industrial area totaling 650 acres and the total roof area for the site was 71 acres. The study modeled the individual effects of adding new trees, vegetated roofs, and green walls to the area and found that the vegetated roofs were able to remove a total of 963 kg of pollutants annually. The breakdown for this figure is as follows: NO_2 (109 kg), SO_2 (30 kg), PM_{10} (443 kg), CO (10 kg), $PM_{2.5}$ (14 kg), and O_3 (357 kg) (Jayasooriya et al. 2017).

A previously researched study in Catania, Italy examined the potential benefits of a vegetated roof on a seven-story building. Findings show this 270 m^2 (2,906 SF) roof would be able to remove 229 kg of CO_2 per year, helping to absorb the emissions generated by just over 3,800 kWh of building heating. Taking the savings of heating and cooling into consideration, there was a total reduction of 240 kg of CO_2 for the roof. Further, the roof would be able to reduce 58.59 kg of NO_2 annually, reducing emissions by 316 kWh (Cascone et al. 2018). These numbers help to quantify the pollutants removed, which would lead to better health of local residents including fewer deaths and respiratory illnesses.

A UK study in Manchester studied the effects of four different species at capturing and removing PM_{10} from the atmosphere. Plants were grown outside the city center and transferred onto two different roofs, one being a three-story building and the other a two-story building. Both buildings were located along a major road in the heart of downtown. The study found that the two species of grasses tested collected the most PM_{10}, with the range of all four plants being able to remove between 0.42-3.21 g/m^2 annually. The study went on to quantify the benefits on a larger scale and modeled out the reductions if all the rooftops within the study area were to be vegetated under the four scenarios. This accounted for 123 acres of rooftop and it was found that the four species would be able to remove between 0.21-1.61 tons of PM_{10} per year for the area, which would reduce emissions by 2.3-17.5% (Speak et al. 2012).

Currie and Bass (2008) studied 72 individual plots within the Midtown district of Toronto in order to quantify pollution removal capabilities of different green infrastructure methods. Using the UFORE method of modeling, seven different scenarios were examined ranging from the baseline case of existing vegetation to the addition of green walls, different methods of tree planting, and vegetated roofs. Findings showed that vegetated roofs added to the existing removal of pollutants the best, being able to remove 1.6 tons of NO_2, 3.14 tons of O_3, 2.17 tons of PM_{10}, and 0.61 tons of SO_2. The total pollution removal value for these numbers came out to be $43,106 CAD per year (Currie and Bass 2008). With health costs due to air pollution in the province of Ontario, Canada estimated to be over $1 billion CAD annually, the findings showed that vegetated roofs are a viable option to help mitigate air pollution within Toronto, especially when they are combined with the existing mitigation effects of the urban tree canopy (Currie and Bass 2008).

A dry deposition model in Chicago aimed to quantify the removal of pollutants by existing vegetated roofs within the city. The study received a list of 170 rooftops from the city and were able to gather more detailed information on 71, creating a combined study area of close to 50 acres of vegetated rooftops (71% of the total vegetated roofs in the city). The results found that in total, 1,675 kg of air pollutants were removed. By assuming the same percentage mix of intensive and extensive roofs on the remaining 29% of rooftops not included in the study, it is estimated that the total city-wide pollution removal through existing vegetated roofs would be 2,388 kg. The most removed pollutant was O_3 at 52%, followed by NO_2 at 27%, PM_{10} at 14% and SO_2 at 7%. The study then found that if all remaining roofs in Chicago were converted to intensive vegetated roofs, pollution removal could reach 2,046 metric tons annually (Yang, Yu, and Gong 2008).

An examination into the potential of vegetated roofs to improve air quality in Washington, D.C. studied both existing and proposed rooftops. With the existing rooftops, the study uses the term “vegetated roof ready”. All existing buildings studied were over 10,000 SF and the term “vegetated roof ready” means the area on each roof which is able to accommodate vegetation. Due to existing rooftops having utilities or other equipment, it is not possible to assume 100% of the roof would be able to accommodate vegetation. Thus, the study assumed an 80% coverage of each existing rooftop which is where the term “vegetated roof ready” comes from. Findings show that if just 20% of the existing rooftops deemed “vegetated roof ready” had vegetation, along with 80% of proposed rooftops, 16.8 tons of air pollutants could be removed from the city annually. This is equivalent to the removal rate of 28,000 street trees. Within the 16.8 tons, six tons would come from the removal of ground-level O_3 and 5.7 tons are from particulates. If 100% of “vegetated roof ready” roofs were converted, the city would see a reduction of 58 tons of pollutants, the equivalent of close to 100,000 street trees. This is a significant number, and yet the number of roofs deemed “vegetated roof ready” is less than 30% of the total rooftops in Washington, D.C. (Deutsch et al. 2005).

There are two ways in which vegetated roofs can reduce atmospheric carbon concentrations: they absorb CO_2 during photosynthesis and they help to create an insulating layer on buildings which limits energy use, lowers the UHI, and reduces carbon emissions (Rowe 2011). A 2014 study examined the carbon sequestration of different plants both at ground-level and planted on vegetated roofs. The plants at ground-level sequestered more carbon, but there were still quantifiable results for the plants on the rooftops. The ability of ground-level plants to sequester more carbon could be attributed to the fact that they have more soil depth for roots to grow and spread out, which allows for the plants to grow larger, or that they were able to spread at a quicker rate than those on the rooftops. It was also estimated that the deeper the substrate is on vegetated roofs, the more carbon the plants can sequester (Whittinghill et al. 2014).

Stormwater / Water Runoff

While traditional roofs designs retain very little water and are efficient at directing drainage into sewer systems, vegetated roofs can help intercept, detain and store rainwater. Vegetated roofs are an ideal solution for stormwater management, as they function on top of pre-existing spaces within urban environments (Oberndorfer et al. 2007). They reduce the peak flow (Moran, Hunt, and Smith 2005), aid in the avoidance of flash flooding, and help to keep pollutants out of water systems. Since the quality of water is generally determined by the surfaces it comes in contact with, vegetated roofs are able to send cleaner water into storm systems. Unlike flat roofs, which can contain pollutants that have settled over time, or other various trash, vegetated roofs help to filter out the water before it leaves the site. Also, runoff from vegetated roofs is cooler than that of flat roofs, and thus helps to limit the spread of bacteria during periods of hotter temperatures (van der Meulen 2019).

The ability for some vegetated roofs to capture and store water more effectively than others is due to its substrate. Roofs with deeper and more porous substrates able to handle more rainwater than those with shallower substrates (Moran, Hunt, and Smith 2005). Also, the size of the roof aids in its ability to retain water and reduce runoff. In Chicago, studies show a 75,000 SF vegetated roof is able to delay runoff by almost two hours, which is longer than observed on other smaller roofs in the area (U.S. General Services Administration 2011b). Areas of the same roof which are not vegetated have a delayed runoff of only 15 minutes or less.

With any vegetated roof, dry soils are able to retain more water than any soils already saturated. Also, the retention capabilities of vegetated roofs are better in light to medium rainfall events, whereas they struggle to retain more water in heavy showers (van der Meulen 2019). A 4” vegetated roof is able to retain an average of 1-1.5 inches of rain, which means that when summer storms arise and a quick shower falls, close to 90% of storms can be retained (U.S. General Services Administration 2011b).

Different factors are able to influence the runoff reduction abilities of vegetated roofs. Intensive and extensive roofs are able to reduce different amounts due to the differing substrate depths, roof slope, and plant material (Rowe 2011). One study found that a 2.5-inch-deep substrate with sedums and grasses is able to retain close to 70% of water (Moran, Hunt, and Smith 2005), while another in North Carolina monitored a roof with a three-inch-deep substrate and found that it retained an average of 63% of rainwater and reduced runoff by 87% (Weiler and Scholz-Barth 2009). Around Washington, D.C. and the surrounding Maryland area, vegetated roofs have been shown to capture and treat on average 85-91% of annual rainfall (Moran, Hunt, and Smith 2005).

In the early-2000s, multiple vegetated roofs were set up in Athens, Georgia at the Boyd Science Library. One was integrated into the existing rooftop, with a soil depth of 3” and a total depth of 4.68”, while the other system was modular. By studying rainfall events from November 2003-November 2004, findings showed that the integrated system had an average retention of just under 78%. When storms were under 0.5”, the roof had a 90% retention rate (T. L. Carter and Rasmussen 2006). This study also found that the typical runoff delay was between 0-10 minutes and that the vegetated roof carried a curve number (CN) of 86. A separate study utilizing the modular system in the same location found its retention rate to be 67% of the average rain event (Tim Carter and Butler 2008).

A second study utilizing the integrated rooftop at Boyd Science Library examined overall stormwater reduction at a watershed level in Athens, GA. For this study, impervious surfaces carried a CN of 98, typical landscape areas received a CN of 84, and the vegetated roof carried the CN of 86. The watershed is 585 acres in size and has a 53.8% impervious coverage (of which approximately 30% is rooftop). Using modeling software, findings showed that if all roofs within the watershed were vegetated, a 3.4% reduction in stormwater would occur for the entire watershed. With only flat roofs being converted, a 1.6% reduction would occur, which equals the interception values of urban forests found in a separate study (Xiao and McPherson 2002). (Timothy Carter and Jackson 2007)

An earlier study examined the benefits of converting “vegetated roof ready” roofs within Washington, D.C. The number of roofs within this category total almost 75 million SF, yet this number is still less than 30% of the total rooftops within the city. If just 20% of these roofs (approximately 15 million SF) had vegetation, they would eliminate almost 300 million gallons (920-acre-feet) of precipitation from the sewer system. Further, it was found that if all the roofs deemed ready for vegetation were converted (74.9 million SF), they could reduce runoff by 68% over conventional roofs, could store 1.485 billion gallons (4,557 acre-feet) of stormwater, and reduce city-wide runoff by 5.8% (Deutsch et al. 2005).

Since many cities do not have separate sewer and storm systems, they can experience a CSO in times of heavy rainfall. By retaining rainfall, vegetated roofs are able to limit the number of CSOs and can help keep untreated sewage out of water systems (Rowe 2011). One of these cities is New York City, where heavy rains cause CSO events to spill an estimated 40 billion gallons (122,755 acre-feet) of untreated waste water into the water systems annually (Elliott 2003).

In Melbourne, Australia, a study simulated rainfall events with different plant species in order to determine vegetated roof retention capabilities. The study ran for over a year and simulated 92 different events. It was found that runoff rates were related to rainfall depth and, on average, the species monitored were able to retain between 89-95% of the simulated rainfall (Z. Zhang et al. 2019).

Liola, Mary, and Pimentel da Silva (2019) studied the retention capabilities of modular tray systems. The study included trays of both vegetated and bare soils and was based in Rio de Janeiro, Brazil. Heavy rain conditions were simulated, similar to an extreme flooding event, which is typical of the local climate. Conclusions stated that the modular systems were able to retain an average of 58% of the simulated rainfall, with an average runoff delay of 12 minutes. The vegetated trays performed best, with average retentions of 63%, while the bare soil trays saw an average of 53% retention (Loiola, Mary, and Pimentel da Silva 2019).

Finally, Palla, Gnecco, and Lanza (2010) studied a 15” intensive roof (7.5” of growing media) in Italy and found that over the course of a 30-rainfall event period, the roof retained an average 51% of water, reduced peak flow by 83%, and delayed runoff by an average of over five hours (Palla, Gnecco, and Lanza 2010).

Energy Reduction

Through looking at the economic and environmental benefits of vegetated roofs, previous sections have briefly touched on some of the energy savings that they can bring both the buildings they adorn, and even some savings for adjacent buildings. According to some research, a 4% electricity reduction can be seen by lowering summer temperatures 1.8°F, which would bring about millions of dollars in energy savings (Cantor and Peck 2008).

In a previously examined study, the i-Tree Eco software tested different methods of green infrastructure on an industrial site in Australia. In terms of energy savings, vegetated roofs provided the greatest energy savings, followed by green walls and then trees. Over the 71 acres of total roof area, vegetated roofs saved $960,000 Australian dollars (AUD), green walls saved $199,000 AUD, and the two combined saved 3,324-megawatt hours (Mwh) annually (Jayasooriya et al. 2017). Another study previously looked at in Catania, Italy found that through modeling different substrates and vegetation, energy demand in the winter decreased by 2-10% and 31-35% in the summer. Further, cost savings due to the reduced energy loads were between 14-19% (Cascone et al. 2018).

A study based in Saudi Arabia looked into the energy savings of three options of vegetated roofs on a residential building. The three modeled options included covering the entire roof (175 m^2 (1,883 SF)), covering one side half, and covering the front half. The base case energy use was 169 kWh/m^2 and it was found that when vegetation covered the entire building, energy dropped 35% to 110 kWh/m^2 for an annual savings of around $310 USD (Mahmoud et al. 2017).

An experimental model carried out in Mashhad, Iran, examined the effects of a sedum roof and a 10-centimeter substrate over a 350 m^2 (3,767 SF) building. It was found that the energy savings during the summer months would be 7.9 kWh/m^2, which was then used to model savings over three scenarios of vegetated roof development (7.8, 45, and 96 million m^2 (~84 million, ~484 million, ~1 billion SF) of coverage). Through these models, findings show energy reductions in the summers could be by 61,620, 355,500, and 758,400 Mwh for each scenario. The best-case scenario would bring about reductions of 52% in the summer months, 21% in the winter months, and 28% overall for the year. Also, as a result of the vegetation, fuel consumption in power plants would be reduced, bringing about savings between $0.7-9 million dollars annually. (Mirzababaie and Karrabi 2019)

While these are specific examples of the benefits vegetated roofs can bring to buildings in terms of energy reductions, actual savings can differ depending on the local climate, the type of vegetated roof installed, and the different building characteristics (Santamouris 2014). While the initial thoughts of vegetated roof development may be focused more on their environmental impacts such as stormwater retention and pollution mitigation, their energy reducing capabilities are also a strong argument for their inclusion on building rooftops. Their role in energy savings not only helps to provide a more comfortable environment, but also reduces emissions from air conditioning and heating as well as providing cost savings for the building owners and urban areas.

Other Environmental Benefits of Vegetated Roofs

Along with the benefits previously described, vegetated roofs can reduce noise, increase biodiversity, and are able to mitigate habitat loss due to urbanization. Due to their vegetative layer, they are able to reduce ambient acoustics from adjacent streets and air traffic (van der Meulen 2019). One study found that vegetated roofs are able to provide a greater transmission loss than bare roofs by up to 10-20 decibels (Connelly and Hodgson 2013). It has also been found that noise reduction is greater when roofs are lower and closer to the source of the sound (Vijayaraghavan 2016).

In some parts of Europe, vegetated roof policy and implementation is driven by the desire to develop wildlife habitats (Cantor and Peck 2008). In a Swiss study, flat roofs were studied in order to determine vegetated roof development in relation to the breeding success of the northern lapwing. The study found that while breeding had been unsuccessful on vegetated roofs, extensive roofs could be planted to mimic grasslands or other habitats in order to provide comparable habitats to ground-nesting birds and other wildlife (Baumann and Kasten 2010).

Social Benefits of Vegetated Roofs

Most of the social benefits come as byproducts of the economic and environmental benefits, but some are stand alone. For example, if a vegetated roof has hardscape incorporated into the design, it could be used as a place for a lunch break or meeting. Vegetated roofs also provide urban greenery which can be viewed and enjoyed by those either working or living above. Benefits which come as a by-product to benefits previously discussed include thermal comfort, better health, and access to urban agriculture. By better insulating building roofs, extreme temperatures within the building can be reduced, helping to keep the climate balanced and reducing the amount of air conditioning or heating being pumped into workspaces. Through mitigation of air pollutants, workers and visitors to the building would have less exposure to harmful air, helping to avoid illness and sick days. Lastly, some residents without access to garden plots or land could utilize vegetated roofs as a form of urban agriculture, growing herbs or other crops.

Through these benefits, vegetated roofs are a very attractive form of green infrastructure to urban areas. Possibly one of the best benefits of vegetated roofs is simply the fact their implementation in urban areas requires no additional land development. There are already millions of acres worth of rooftops within urban areas serving as blank canvases for vegetated roof to provide artwork to. Another overarching benefit for vegetated roofs is the fact that they are able to provide so many benefits to humans, the environment, and buildings. Alternative forms of sustainable design to exist, such as white roofs, solar panels, or rain barrels, however each of these only accommodates one or two benefits each. White roofs benefit the UHI and help to keep building temperatures lower due to their ability to reflect sunlight back into the atmosphere and their low heat storage. Solar panels can create energy for buildings, helping to cut utility costs to the building. Rain barrels can capture stormwater and keep it out of storm sewers temporarily, however they will still need to be emptied when full. While all of these are great options if the desired benefit is tailored specific to their uses, vegetated roofs are able to accomplish the benefits of all three, plus they can remove pollutants from the atmosphere, sequester carbon, add oxygen back to our urban areas, buffer sound, add to a building's real estate value, and much more.

Arguments Against Vegetated Roofs

While there are many benefits and arguments for the inclusion of vegetated roofs within urban spaces, there are also arguments against their development. Some of the most common reasons for not developing vegetated roofs are because of the high initial costs of implementation, lack of incentives for their development, and a lack of knowledge about their benefits. Other reasons include uncertainty regarding the structural abilities of existing buildings, the need for added structural capacity on planned buildings, added maintenance costs, design issues, existing roof slope, technical issues, or questions regarding ownership once developed.

As to the initial higher construction costs, it is true that vegetated roofs cost more than traditional flat roofs. In most cases, flat roofs cost between $7-$15 USD/SF, whereas vegetated roofs, depending on their type and makeup, can run from $15-$70 USD/SF (Moran, Hunt, and Smith 2005). Extensive roofs fall on the lower end of the cost range, as they do not require as deep a system. For a multi-course extensive roof, the average cost is between $10.30-$12.50 USD more per square foot compared to a conventional roof (U.S. General Services Administration 2011b).

This main argument can be augmented by proper education of the cost savings benefits of vegetated roofs. While the cost is higher for vegetated roofs, their typical lifespan far outnumbers that of a conventional rooftop and studies have found that with the annual savings due to their inclusion, they are able to pay for themselves over a certain number of years. One study found that a roof on top of a residential building became net positive at the end of its 19th year (Mahmoud et al. 2017), while another study found that, depending on the medium, the initial cost recovery was between 13.4-17.9 years for the roof (Cascone et al. 2018).

Higher costs of vegetated roofs are due to more materials needed, not as many contractors being able to install the roofs, and a lack of education. If there was more widespread education on vegetated roof development, more implementation may happen in urban areas, bringing more contractors and companies to offer vegetated roof installation services. This is similar to how it is in Germany, one of the leading pioneers of vegetated roof development. Due to the widespread implementation within the country, there are more incentives to specify vegetated roofs, more contractors and suppliers who have access to materials, and cheaper installation costs. In the United States, one study found that the average installation of 1 m^2 (10.76 SF) of vegetated roof was $47.30 USD, whereas the same size in Germany was $18.50 USD (Philippi 2006).

As discussed in the policy section, different municipalities have used different incentive programs in order to kick-start their city into developing vegetated roofs. From stormwater credits to grants and added square footage for the total building, these incentives can come in many different forms. Generally, lack of incentives also falls into the lack of knowledge category. Without proper knowledge about the benefits of vegetated roofs, many governments do not have a proper program in place which incentivizes their inclusion into projects.

Without proper knowledge about the benefits of vegetated roofs, it is easy to focus on the arguments against their inclusion. If everyone knew that they outperformed the lifespans of conventional roofs and offered positive economic gains near the 20-year mark, they may have a fighting chance of coming into the conversation earlier. If results on their ability to provide energy savings or ease pressure on storm sewers were more widespread and discussed, incentive programs for their inclusion may become more common. If their health or cooling benefits were more public knowledge, or their ability to add to a building's real-estate value and rent, maybe green spaces would start to top urban buildings more frequently.

Summary of Benefits of Urban Trees and Vegetated Roofs

This thesis originally laid out two main objectives. The first objective aimed to research and determine the potential for vegetated roofs to offset the loss of the urban tree canopy due to construction. Briefly examined was a global history of urban development and population growth, followed by a review on climate issues past, present, and future. From there, the dangers of climate change from economic, environmental, and social standpoints were examined. These sections aimed at providing a crash course of what humanity's actions are doing to both the planet and humankind. The first and most common use of green infrastructure, urban trees, was researched from a historical standpoint in order to understand how environmental concerns were handled in the past. A history of vegetated roofs and how they began both out of necessity in Scandinavia and as an amenity in the Middle East was examined. It was not until very recently in history that vegetated roofs have entered into the conversation of mitigating climate issues and have begun to be installed for environmental purposes.

Next, quantifiable results and benefits of both urban trees and vegetated roofs reviewed the pros and cons of each, while trying to determine the capabilities of vegetated roofs to offset the loss of urban trees as cities expand. Since cities are continually expanding and are topped with conventional roofs, does it make sense to incentivize or mandate the use of vegetated roofs for the sake of health as well as the health of urban areas? Would vegetated roofs provide the same ecosystem services to cities as trees? Would this even be economically feasible? These are all questions that the previous two sections have attempted to research in order to understand the total benefits of vegetated roofs.

Compared with urban trees, vegetated roofs excel in some categories such as stormwater management and retention, and lag behind in others, such as air pollution removal. While vegetated roofs are able to capture and sequester positive amounts of air pollutants at a great service to human and environmental health, large trees are able to provide the same services with greater total capture at a fraction of the cost and on a smaller footprint.

One question not previously asked but discussed below is to what extent could vegetated roofs supplement urban trees in order to even further remove air pollutants, retain stormwater, and mitigate UHI? Could vegetated roofs still be incentivized to the extent that they are developed along with the urban canopy in order to fight climate change more so than they are now? While discussing some of the gaps between vegetated roofs and trees, this section examines the ability for both methods of green infrastructure to work together and what some of the situations and results could look like if they did.

As previously reviewed, both trees and vegetated roofs are able to positively affect the greater temperatures within urban areas. Trees help to cool cities in many ways: they provide shade for the ground level and sides of buildings, help to shade people, increase solar reflectivity, and provide evapo-transpirative cooling. All of these benefits help to combat the increased temperatures within cities. Vegetated roofs are also able to cool cities, but in slightly different ways. Extensive roofs provide cooling mainly for the building roof and areas within six vertical feet of the roof surface. Intensive roofs are able to provide the same, as well as potentially some cooling at ground level if they are on a low enough building and feature taller plants or trees which could throw shade over the side of the building edge. Their temperature reduction abilities for different surfaces depend heavily on their design (Coutts and Harris 2013).

Like trees, they can increase solar reflectivity if they are healthy, and they can also provide evapo-transpirative cooling, but only if irrigated or if it has recently rained and they have water (Norton et al. 2015). Overall, their best chance to reduce surface temperatures is with taller vegetation and irrigation. Even though vegetated roofs are more singular in use than street trees and not part of a giant system within cities, studies have found that they do have the ability to affect temperatures at a neighborhood level, but they must cover a larger area and not just one roof here or there (Rosenzweig et al. 2006).

A study out of Melbourne, Australia used thermal sensing to assess the influence of different surfaces on urban temperature in order to determine the best urban cooling methods. They found that a 10% increase in vegetation could lead to a reduction of 1°C and that different surfaces helped to reduce temperatures at different times of the day. During the day, tree cover and irrigated grass provided the greatest temperature reductions, while at night the reductions were best seen through irrigated and non-irrigated grass. During the day, tree canopy measured an average temperature of 41.59°C, while irrigated grass was 42.81°C. At night, irrigated grass had a temperature average of 25.59°C and trees saw an average of 26.62°C (Coutts and Harris 2013). Through these numbers, findings show the top of the tree canopy was not only cooler than surrounding surfaces, but through the shade provided, the ground surfaces below were cooler as well. While grass surfaces were cooler than surrounding areas, their inability to provide shade hindered their ability to compete with trees. Another aspect of the study looked at the influence of height to width ratio of buildings and adjacent streets. It found that when the ratio was low and there were wider streets, trees were most effective. When the ratio is higher, and some of the street cooling and shade is provided by buildings, trees still do help in the overall reduction of air temperature but are less effective (Coutts and Harris 2013).

When these scenarios arise and a building either provides most of the shade needed at street-level or is only adjacent to the street on its north side (in the Northern Hemisphere), perhaps vegetated roofs would be a better investment to the city. If trees are going to be shaded full-time, they will still provide some ecosystem services, but not to the best of their abilities. Instead of spending the money for their implementation when the street would be shaded and cooled by the building, the investment could then switch to the roof, where greater results in energy savings, stormwater retention, or air pollution mitigation could be achieved. This could be the case in larger cities such as New York City, Chicago, Tokyo, or Seoul, where land is limited and the cities are full of high-rise buildings. In a city such as Atlanta, where there is more land, these situations could arise on more of a case-by-case basis depending on surrounding developments.

In Hong Kong, China, a study found that a vegetated roof on a 60 meter building was not effective in providing any thermal comfort for those at ground-level, nor would 100% coverage of available rooftops be able to benefit those at ground-level (Ng et al. 2012). While they may influence building roof temperatures, energy use, and air temperatures within six vertical feet of the building roofs, their presence would not be immediately felt on the street. For trees, however, it was found that a 16% increase in coverage would reduce temperatures by around 0.4 Kelvin (K) and a 56% increase would see reductions of surface temperatures of up to 1.8 K (Ng et al. 2012).

A 2009 model in New York City examined six different methods of green infrastructure over different heat waves from 2002. Street trees and vegetated roofs were two of the six methods and the study assumed 100% coverage for the available area. While both methods contributed to lower temperatures, vegetated roofs outperformed street trees. However, this was for New York City, where rooftops far outnumber the amount of available street tree planting possibilities. Out of the seven areas studied, impervious surfaces ranged from 60-94%, and the street tree planting method only accounted for 7% of the total city area (Rosenzweig et al. 2009).

The study then adjusted the total cooling benefits for each method on a per-unit-area basis. This adjustment found trees to be able to provide larger cooling benefits than vegetated roofs. Trees, on average, could provide an individual reduction of 1.9°C while vegetated roofs could provide an individual reduction of 1.4°C. Since the city is not able to accommodate mass tree plantings, findings show the best method of reducing the urban temperature for New York City would be through a mix of trees and vegetated roofs. With this strategy, temperatures reductions could range from 0.4-0.7°C. Also, a benefit of this strategy is through reduced costs in power and electric rates. These savings could be more than $1 billion USD over the 35-year lifespan of the strategy (Rosenzweig et al. 2009).

When it comes to the ability for trees and vegetated roofs to remove air pollutants, Sicard et al. (2018) found that vegetated roofs removed less O_3 than trees did, at a rate of 2.9 g/m^2 compared to 3.4 g/m^2. Another study out of Melbourne, Australia found that through different green infrastructure scenarios, vegetated roofs could remove 357 kg of O_3 per year, while trees would be able to remove more than five times that at 1,885 kg per year (Jayasooriya et al. 2017). This particular study found that in every situation, trees out performed vegetated roofs in total kg of pollutants removed, except for the removal of CO, where it was found that both remove the same amount. Even though the total kg was higher for trees, vegetated roofs had a higher percentage uptake for PM_{10}, meaning that in industrial areas they could be the most viable method of green infrastructure to help combat air quality issues (Jayasooriya et al. 2017).

Another study from Toronto, Canada found that the existing trees and shrubs remove 10.7 tons of O_3 per year. By adding vegetated roofs to all available surfaces in Midtown, an extra 3.1 tons would be removed per year (Currie and Bass 2008). The study further stated that trees were the most important strategy for removing pollutants and that vegetated roofs could complement the removal rates, but could not match them. In a full build-out model performed where vegetation covered all available rooftops, it was found that trees outperformed vegetated roofs in every air pollution removal category. The removal rates for vegetated roofs were very similar to those of existing shrubs, but only around half that of trees (Currie and Bass 2008). Intensive roofs would be able to play a larger role than extensive roofs, but they still would not be able to total the air pollution removal by trees. Lastly, it was also found that the removal rates of extensive roofs were not linear with their implementation. A 100% coverage scenario did not equal five times the benefits of a 20% scenario (Currie and Bass 2008). This could be due to a few factors, such as the different heights and locations of building roofs and the fact that lower roofs can be shaded more often and might not be able to provide the same removal rates as higher unobstructed rooftops. Although the results did not show that vegetated roofs were comparable to urban trees, it helped to illustrate the positive effects they could still have to the city when combined with the use of trees.

Speck et al. (2012) aimed to identify PM_{10} removal by four different vegetated roof species on two rooftops in Manchester, UK. They found that red fescue (*Festuca rubra*) was able to capture the most PM_{10}, with a total of 3.21 g/m^2 annually (Speak et al. 2012). In comparison with trees, that removal rate is actually fairly close to the results from a 2006 study. Out of 55 cities in the United States, PM_{10} removal ranged from 0.4-12.6 g/m^2. In Atlanta, the range was 1.5-5.9 g/m^2 (Nowak, Crane, and Stevens 2006).

A previous study reviewed ran different scenarios for greening Washington, D.C. One of the scenarios called for adding vegetated roofs on all "vegetated roof ready" buildings, totaling almost 75 million SF. The total pollutant removal from this scenario would be 58 tons (t) annually (Deutsch et al. 2005). For a comparison on pollutant removal by trees in Washington, D.C., Nowak, Crane, and Stevens (2006) showed that urban trees remove 558 t of pollutants annually. In Atlanta, that number is 1,200 t.

One area where vegetated roofs provide greater benefits than trees is with stormwater capture and retention. Depending on the type of system and composition of the substrate, vegetated roofs can reduce runoff from 50-100% (Rowe 2011). A study in Washington, D.C. examined different greening methods with vegetated roofs and trees, where moderate and intensive methods of planting were both modeled. In the intensive scenario, it was assumed that 102 million SF of roofs would be converted to vegetated roofs, accounting for 40% of the total building area in the city. For trees, the intensive scenario called for the total coverage to rise from the existing 35% to 57% throughout the city. In order to achieve one million gallons (3-acre-feet) of stormwater reduction, 2.56 acres of vegetated roof coverage would be needed. For trees, the best-case scenario for the same reduction would be nine acres (Deutsch et al. 2007). The study also found that for each incremental percentage increase, tree cover over impervious surfaces would increase reduction by 11 million gallons (33-acre-feet), while vegetated roofs would increase reduction by 17 million gallons (52-acre-feet). Also, the intensive scenario increases tree cover by 4,300 acres. This increase helps to reduce stormwater and CSO discharges by 193 million gallons (592-acre-feet) annually. The intensive scenario increase in vegetated roofs sees an addition of only 2,295 acres of vegetation and the combined discharges are reduced by 882 million gallons (2,706 acre-feet) annually (Deutsch et al. 2007). Although trees outperform vegetated roofs in terms of air pollution removal, this study helps to quantify the ability for vegetated roofs to outperform trees when it comes to reduction in stormwater runoff.

When it comes to the economics of trees and vegetated roofs, there is not much of a contest. Individual trees do not cost much on a per unit basis, whereas the cost is much higher for vegetated roofs. In Chicago, it one study stated that if all remaining rooftops were converted to extensive roofs, it would cost $22 billion USD. If those were to be intensive roofs, the cost would be over $35 billion USD (Yang, Yu, and Gong 2008). 19 m^2 (204 SF) of extensive vegetated roofs can provide the same reduction in air pollutants as a medium sized tree; however, the cost is what sets the two apart. Where the tree comes in around $400.00 USD, the vegetated roof would cost the developer over $3,000 USD (Yang, Yu, and Gong 2008). Aside from that, the annual costs, which include operation and maintenance, per kg removed of O_3 for an urban tree is around $300.00 USD, while a vegetated roof is around $600.00 USD (Sicard et al. 2018).

One of the added fees associated with the development of vegetated roofs is in their design. Extra attention and expertise are required to ensure they are designed and implemented properly. If a roof is vegetated and it does not function properly, the investment is essentially wasted. On the other hand, as long as a tree has proper root space, light, and water, it can grow and contribute ecosystem services to the urban environment. Vegetated roofs require more care in order to make sure they grow to their full potential and are providing expected services.

In the Melbourne, Australia study reviewed throughout these past sections, costs were compared between vegetated roofs looking at capital costs, maintenance, and building energy savings. Vegetated roofs far outperformed trees when it came to energy savings for the industrial site, bringing in an annual savings of over $960,000 AUD compared to just $26,000 AUD for trees. The overall capital costs, however, were very much different. Where trees would cost $2.3 million AUD and had annual operation and maintenance fees of just under $500,000

AUD, vegetated roofs had annual costs of over $43 million AUD, with operation and maintenance fees of just over $2 million AUD (Jayasooriya et al. 2017). Even though these costs are vastly different, vegetated roofs still could have an argument for inclusion based on their energy savings potential on the industrial site.

If a city were looking into green infrastructure methods to reduce air pollution, the much higher costs of vegetated roofs almost makes them economically unfeasible (Yang, Yu, and Gong 2008). However, given their stormwater capabilities, building energy savings, and longer life spans, vegetated roofs are able to provide many long-term economic benefits. These help keep vegetated roofs in the picture and help make a case for their inclusion within urban areas.

Even though the initial installation costs are much higher with vegetated roofs and they may not provide a direct replacement for urban trees, there are still many arguments for their inclusion within urban areas. The space is already available for them, as cities have millions of square feet of conventional, bare rooftops. When in mass, vegetated roofs can have positive impacts on the UHI, greatly reduce stormwater runoff, help to avoid CSO damage and pollution, and can supplement urban trees in the reduction of air pollutants. These benefits, along with their added lifespans, energy savings, and ability to pay for themselves over time, show that serious consideration should be given for their implementation in urban areas. With the climate changing, cities expanding, and space for urban trees vanishing, rooftops present an area of considerable potential.

CHAPTER 3

METHODS

The second research question of the thesis examines the overall ecosystem services and benefits which vegetated roofs can bring to Atlanta. In the section to follow, the main methods of research are through precedent studies and projective design. Precedent studies help to gain better understanding on existing projects around the world, as well as the state of Atlanta's vegetated roofs compared to other cities worldwide. Projective design illustrates the site-specific benefits of expanding a 20,000 SF extensive vegetated roof in Atlanta through different adoption rates of vegetated roof coverage in Atlanta before extrapolating those results across different adoption rates within the city.

Precedent Studies

When research for this section began, it was difficult to decide how many projects to include, as well as the specific criteria for each project. This section is mainly arbitrary, with no specific correct answer as to how to compile a list of projects to include. Whether it was decided to include award-winning vegetated roofs, socially popular vegetated roofs, or the most ecologically friendly, any list would be much too long for this section. In the end, I decided to select five projects from three geographical categories; international, domestic, and the city of Atlanta. This allowed for a better mix of projects and ensured that one city or country could not dominate the list of precedents. The overall goal of selection was to include a mix of projects or cities either previously mentioned within this thesis or which include interesting designs or approaches to vegetated roof design which could be marquee projects if implemented in Atlanta.

The first step in selection was searching the online database of vegetated roofs at greenroofs.com (Greenroofs.com 2020). They have a project database updated with information about many vegetated roofs around the world, including information on size, type, architect, and facts related to the roof's performance. For the international projects, the selection was the most difficult of all three categories, as it represents the largest geographical category. As Germany is one of the leading countries for vegetated roofs in the world, five projects could have been detailed from many of their major cities. Instead, only one project from the country made the list, the Frankfurt International Airport. I selected this project due to Atlanta having the busiest airport in the world and to highlight the possibilities of vegetated roofs on any type of building, not just office, retail, or residential.

I chose Nathan Phillips Square due to its prominence within the city of Toronto and its history in their vegetated roof pilot program. Selection of the Vancouver Convention Center was due to its innovative design and popularity in the green infrastructure world. Hailed when first opened, the building is a compliment to the city and can serve as an inspiration to similar buildings around the world. I selected the other two projects, the ACROS International Hall and the Nanyang Technological University buildings, based on both their geography as well as their innovative use of vegetated roof design. Often, vegetated roofs are thought of as places off-limits and away from public access. These two roofs invite the viewer onto the roof to experience the design first-hand.

In looking at domestic examples of vegetated roofs, one driving force for project selection was looking at cities previously highlighted in this thesis. Rooftops in New York City, Chicago, and Washington, D.C. are included, as well as the Ford truck plant in Dearborn, Michigan. This project was known all around the landscape architectural world when it first was implemented and continues to be an excellent example of an extensive vegetated roof today.

Although other cities such as Portland, San Francisco, and Philadelphia have championed vegetated roof development and have many examples of vegetated roofs worth further study, these are not included within the precedents.

Atlanta precedents are a little more limited in selection. Information is very difficult to come by relative to some of the other projects stated above. While there are multiple sources online which list out different vegetated roofs around the city, some projects on those sites are either no longer in existence or have been so poorly maintained that little to no information is available. In the end, the selection criteria for Atlanta was based on a mix of buildings which many Atlantans will be familiar with and available information online.

Projective Design

Within the projective design phase of the thesis, I carried out a review of the literature in order to gain knowledge about formulas used in calculating individual benefits of vegetated roofs. Along with these individual formulas, different computer programs including the Landsat Explorer App from ESRI's Change Matters website (ESRI 2020), ImageJ (ImageJ n.d.), Google Earth (Google 2020b), and Adobe Photoshop (Adobe 2020) were used in order to calculate area coverage of different land uses/land covers and to help visualize the results of the calculated benefits. The Landsat Explorer App utilizes satellite imagery captured every 16 days in order to visualize change which can occur in vegetation, urban areas, water, or other areas of study on a particular site (ESRI 2020). For each figure analysis throughout this thesis, I searched for Atlanta in Landsat and zoomed the screen to fit the entirety of the city limits. Landsat allows the user to select between different layer masks and different image dates, which have been saved out for vegetation coverage and urban index areas for the city of Atlanta between 2000 and 2019 (ESRI 2020). The images were taken into Adobe Photoshop and trimmed so that the only information was within the city limits of Atlanta (Adobe 2020). From here, the images were turned to black and white and loaded into ImageJ, a java-based computer program which allows area calculations of images (ImageJ n.d.). Inside ImageJ, the image is opened and in order to calculate the area, the user must click on 'adjust' and then 'color threshold'. Once this opens, the negative space of the image will turn the color selected from the dropdown box, which defaults to red. By clicking 'select' and then 'analyze' and 'measure', the area is given of any space previously shown in red. In the original image box, pixel sizes are given at the top left-hand corner. By multiplying these together and subtracting the area just calculated, one can gather the total area remaining. In this case, the area remaining was always what was needed for area and percentage calculations. For example, if the area of everything in red totaled 2,000 and the image was 400x400 pixels, the remaining area of the image is 158,000. When all calculations were made for this thesis, one piece of information needed was the total area, in pixels, of the city limits of Atlanta. Once this was found, each calculation of area found after (building coverage, vegetation coverage, urban areas) was divided by the area of the city limits in order to calculate percent coverage. When the final graphics were put together, Google Earth (Google 2020b) was used to save aerials of Atlanta, which were then inserted to scale behind all graphics in photoshop (Adobe 2020).

Sample Roof Calculations

The first step in quantifying benefits of vegetated roof development in Atlanta is to set up a standard roof size for the following equations. In a typical master planning exercise, office buildings typically assume a 25,000 SF floorplate laid out at 120x210 feet. The limits of vegetation would not extend to the edge of any roof developed with a vegetated roof. There would need to be access for maintenance purposes, as well as areas for any needed mechanical equipment. These needs assume the use of 20% of the rooftop, which leaves 80% (20,000 SF) available for the development of an extensive vegetated roof.

Energy Savings

Multiple methods aid in the calculation of energy savings. First, a formula suggested by the Center for Neighborhood Technology (CNT) allows for calculations of heating and cooling savings through the following equations:

Annual heating savings (Btu/SF) =

$$Annual\ number\ of\ heating\ degree\ days\ (°F) * 24\frac{hrs}{day} * \Delta\text{U} \tag{1}$$

Annual cooling savings (Btu/SF) =

$$Annual\ number\ of\ cooling\ degree\ days\ (°F) * 24\frac{hrs}{day} * \Delta\text{U} \tag{2}$$

(Center for Neighborhood Technology 2011).

Both heating and cooling savings are calculated in British thermal units (Btu) and depend on geographic location. Heating degree days (HDD) and cooling degree days (CDD) are calculated by using a pre-determined degree F temperature and measuring any days in which the temperature either rises (cooling degree days) or falls (heating degree days) below that degree. This determines how often heating and cooling systems must work in order to keep a building temperature at a set level, usually calculated at 65°F. For example, if the average temperature for a day is 82°F, that day has a CDD of 17. If the average temperature on a given day is 40°F, that day has an HDD of 25. All days of the year are added up in order to determine the total HDD and CDD which helps to determine the annual savings for vegetated roofs. For this calculation, data on HDD and cooling degree days CDD was collected from the National Weather Service Forecast Office. Daily data was collected for Atlanta between January 2019-December 2019 in order to calculate the total HDD and CDD for the year (National Weather Service 2020).

The second part of the above equation that needs to be determined is ΔU. Here, U is equal to the heat transfer coefficient, which is an inverse of R, a thermal resistance value. This value determines how well a given material resists heat flow, or how well it is insulated. A higher R-value signifies better insulation (U.S. Department of Energy n.d.). The CNT calculates R values as:

the units of square feet * °F * the hours/Btu=

$$(SF * {}^{\circ}F * \frac{hrs}{Btu}) \quad (3)$$

(Center for Neighborhood Technology 2011).

According to one study, conventional rooftops carry an R-value of 11.34 SF * F * hrs/Btu and typical 4” vegetated roofs have an R-value of 23.4 SF * F * hrs/Btu. The same study calculates that for every centimeter (cm) of growing media, the R-value increases or decreases by 1.2 SF * F * hrs/BTU. Thus, a modular vegetated roof with a soil depth of 2” would carry an R-value of 17.4 SF * F * hrs/Btu (Clark, Adriaens, and Talbot 2008). ΔU is calculated as follows:

$$\Delta \mathrm{U} = \left(\frac{1}{\mathrm{R}_{ConventionalRoof}}\right) - \left(\frac{1}{R_{VegetatedRoof}}\right)$$

$$\Delta \mathrm{U} = \left(\frac{\mathrm{Btu}}{11.34\ \mathrm{SF}{*}{}^{\circ}\mathrm{F}{*}\mathrm{hrs}}\right) - \left(\frac{Btu}{23.4\ SF{*}{}^{\circ}F{*}hrs}\right) \quad (4)$$

With ΔU and information on the HDD and CDD defined, these are inserted into (1) and (2) in order to determine energy savings per SF. When determining cooling reductions, the final result is multiplied by 1/3,412 in order to convert Btu into kWh. Once both savings are expressed in kWh, they are multiplied by the total square footage, which will yield the annual benefits for a 20,000 SF extensive vegetated roof in Atlanta.

Air Pollution

Similar to that of energy reduction, I studied air pollution calculations through a review of the literature. The type of vegetated roof constructed, either extensive or intensive, can make a difference in the amount of air pollutants removed from the atmosphere. This is mainly due to the leaf area index (LAI) and the depth of soil. The LAI is the measure of the area of leaf surface/the area of ground cover of a plant, usually expressed as m^2/m^2. Generally, intensive vegetated roofs have a higher LAI due to the variety of plants available for use. Since extensive roofs are usually sedums, lower ground covers, or grasses, they have a lower LAI.

Currie and Bass (2008) and Yang, Yu, and Gong (2008) both studied air pollution mitigation by vegetated roofs. Through their two results, a range of air pollution values was determined for different pollutants. These values are based on plant material, from grasses to tall herbaceous plants. For O_3, a vegetated roof can be able to remove between .267-.540 grams/square feet (g/SF) of pollutants. For NO_2, the range is .136-.273 g/SF, SO_2 has a range of .060-.184 g/SF, and PM_{10} is between .052-.141 g/SF. These number can vary, similar to energy savings, based on location of the vegetated roof, type of roof used, and plant material. In order to find a range of pollution reduction for the test roof in Atlanta, the numbers above are multiplied by the total square footage of the vegetated roof.

Not only is pollution removal calculated by what the plants can capture from the air, but also through the reduced need of electricity throughout the year which was previously calculated. The EPA has calculated state output emission rates for various pollutants from 2018, which are multiplied by the total energy savings from the vegetated roof to estimate how many air pollutants are avoided through the running of building energy. According to the EPA, Georgia emits .420 kg/kWh of CO_2, .000036 kg/kWh of methane (CH_4), .0000054 kg/kWh of N_2O, .000181 kg/kWh in NOx, and .000136 kg/kWh of SO_2 (U.S. Environmental Protection Agency 2020d).

Along with electricity savings, the EPA also has data on the annual input emission rates throughout the United States. According to their report, Georgia emits 69.832 kg/million Btu (MMBtu) of CO_2, .00589 kg/MMBtu of CH_4, .00091 kg/MMBtu of N_2O, .0336 kg/MMBtu of NO_x, and .0231 kg/MMBtu of SO_2 annually (U.S. Environmental Protection Agency 2020d). The data for electricity and emission rates can be multiplied by the heating and cooling reductions previously calculated in order to calculate pollutants avoided due to energy savings. These numbers are then added to the range of pollutant removal via the plant material in order to calculate total air pollutant removal of the vegetated roof.

Carbon sequestration capabilities of the vegetated roof also need calculation. Two studies performed in Maryland and Michigan looked at the ability for extensive vegetated roofs to sequester carbon through different plant material. The first study, conducted over 12 different rooftops, found carbon sequestration of the aboveground plantings to range between 73 g/m^2-276 g/m^2 with an average of 162 g/m^2 (15.05 g/SF) (Getter et al. 2009). The second study examined four rooftop extensive systems and found the range of C sequestration to fall between 64 g/m^2-239 g/m^2 with an average sequestration of 168 g/m^2 (15.61 g/SF) (Getter et al. 2009). The disparity of values between all the extensive vegetated roofs are due to different plant selections.

For the vegetated roof calculation in Atlanta, I assumed an average of 15.33 g/SF (.01533kg/SF). Multiplying this by the total size of the vegetated roof gives the total amount of C that the rooftop could sequester annually. In order to add this number to the CO_2 benefit calculated earlier, the sequestration of C needs to be converted to CO_2. This is done by multiplying C by 3.67, which gives a result of removed CO_2 through the annual sequestration of C. This is added to the range of CO_2 calculated previously to get a total amount of removed CO_2 from the vegetated roof.

Economic value is placed on the vegetated roof in terms of removed and avoided pollutants from the atmosphere. Multiple studies have researched associated removal values of different pollutants. The USDA Forest Service has valued NO_2, SO_2, O_3, and PM_{10}, another study has quantified the values of CH_4 and N_2O, while another two have averaged the cost of CO_2 removal. These values are multiplied by the kg removed and avoided in order to gather total economic benefit of the vegetated roof. Costs associated with each pollutant are as follows:

NO_2 – \$14.44/kg

SO_2 – \$4.21/kg

O_3 – \$14.59/kg

PM_{10} – \$5.09/kg

(McPherson et al. 2006)

CH_4 – \$0.41-2.20/kg

N_2O – \$3.86-31.97/kg

(Marten and Newbold 2012)

CO_2 – \$0.0167-0.085/kg

(Center for Neighborhood Technology 2011) (Haight et al. 2020).

Stormwater Reductions

For stormwater reduction calculations, a thorough review of the literature was conducted in order to determine different retention percentages for different types of vegetated roofs. Through this review, I found that there is no absolute percentage of retention or runoff for each type of vegetated roof. A matrix of studies and average retention rates (Table 4) summarizes studies researched for the 20,000 SF rooftop in Atlanta.

Table 4: Average retention percentages of vegetated roofs through reviewed studies

Authors	Roof Type(s) / Depth(s)	Rainfall Total	Average Retention
Berghage et al. 2009	4"	111 events, 9 events over 0.5"	54%
Deutsch et al. 2005	Extensive	N/A	65%
Deutsch et al. 2005	Intensive	N/A	85%
Deutsch et al. 2005	80% Extensive 20% Intensive	N/A	69%
Hilten, Lawrence, and Tollner 2008	4" Modular	Up to 0.5", 1", 1.5", 2", 3.12"	100%, 65.6%, 44%, 33.3%, 21.6%
Loiola, Mary, and Pimentel da Silva 2019	(3) Modular systems 1-3"	N/A	58%
Mentens, Raes, and Hermy 2006	Extensive / Intensive	N/A	45% / 75%
Moran, Hunt, and Smith 2005	2.5-4.25"	N/A	63-95%
Palla, Gnecco, and Lanza 2010	15"	N/A	51%
Scholz-Barth 2001	1-4"	N/A	58-71%
Weiler and Scholz-Barth 2009	2.5-4.25"	N/A	63-95%
Z. Zhang et al. 2019	2.5-4.25"	N/A	63-95%

One study examined three different modular-tray systems ranging from 1”-3” in depth. Each system was tested with both bare soil and vegetation and results found that retention percentages ranged from 33%-73%, with an average of 58% (Loiola, Mary, and Pimentel da Silva 2019). Another article studied a modular system which was just under 4” and found that retention was 100% for storms up to 0.5”. The study modeled storms at 1”, 1.5”, 2”, and 3.12” and found retention to be 65.6%, 44%, 33.3%, and 21.6%, respectively (Hilten, Lawrence, and Tollner 2008). Berghage et al. (2009) built three test vegetated roofs with 4” profiles and recorded rain events for 2005. Over the course of 111 events, nine of them had rainfall totals greater than 0.5”. Out of these nine, the average retention for the vegetated roofs was 54% (Berghage et al. 2009). Scholz-Barth (2001) found average retention percentages between 58%-71% for rooftops with growing media between 1”-4”. Moran, Hunt, and Smith (2005), Weiler and Scholz-Barth (2009), and Z. Zhang et al. (2019) all studied extensive systems ranging from 2.5”-4.25” inches in depth and found retention to be between 63%-95% for those systems. In Washington, D.C., both extensive and intensive systems were monitored and it was found that, on average, extensive systems retained 65% of stormwater, intensive systems averaged 85% retention, and an 80% extensive 20% intensive mix of vegetated roof types could yield an average retention of 69% (Deutsch et al. 2005). Mentens, Raes, and Hermy (2006) state that through review, intensive roofs retain an average 75% of rainfall and extensive roofs retain 45% while Palla, Gnecco, and Lanza (2010) studied 30 rainfall events on a 15” intensive roof (7.5” of growing media) in Italy and found that the roof retained an average 51% of water. The bottom line is that there is no one answer for each type of roof.

Although many studies have found that extensive vegetated roofs are able to retain 70% and greater of stormwater which falls on the roof, some studies are lower. This could be due to different plant material, climate, or total rainfall for each event. For this reason, this thesis will assume an average 65% retention rate for the extensive roof.

The first step in gathering stormwater data for vegetated roofs is to compile both the retention rate and the average precipitation of a given site. While yearly rainfall in Atlanta fluctuates greatly, from 38.69 inches in 2016 to 70.03 inches in 2018, over the past 30 years the city has averaged 49.17 inches of rainfall (U.S. Department of Commerce 2020). By taking this information, calculation of the annual runoff reduction is as follows:

$$annual\ precipitation * roof\ area\ (SF) * retention\ rate\ (\%) * 144\frac{inches}{SF} * \ .0043\frac{inches}{cubic\ foot} \tag{5}$$

The Center for Neighborhood Technology has put a cost to the avoided stormwater treatment due to vegetated roofs, calculated at $29.94 per acre-foot (Center for Neighborhood Technology n.d.). This is the measure of what it would take to cover an acre of land with one foot of water, which equates to 325,851 gallons. The reduced stormwater calculated from the 20,000 SF roof will be divided by 325,851 and multiplied by $29.94 in order to determine the cost benefit of avoided water treatment costs.

Scaled Calculations and Adoption Rates

The next step is to take the individual benefits found for the vegetated roof in Atlanta and scale them up based on different adoption rates of vegetated roof coverage. This will better help to answer the second question of the thesis. In order to be able to forecast more city-wide results, the number of available rooftops is needed.

The City of Atlanta’s Department of Planning’s website has reference material which includes multiple GIS files and maps. One of the files available is information on building footprints throughout the city. This file, last updated in 2018, contains a spreadsheet and shapefile which map out where each building is located within the city limits. I overlaid this file onto a Google Earth aerial of the city in photoshop in order to better visualize building coverage throughout the city (Figure 8).

Although the spreadsheet has tabs for information such as year built, height, type, and other categories, the only information given is the area square feet of each building. For 104,598 buildings listed, the total cumulative area of buildings in the city is 386,666,837 SF (City of Atlanta 2018). This is important to know, as it will be multiplied by the percent coverage of different zoning categories identified by the city of Atlanta in order to understand the total available rooftop square footage for each category (commercial, mixed-use, etc.).

The City of Atlanta's Office of Zoning and Development consolidated all zoning within the city into nineteen different land use under the umbrella of nine major categories (Department of Planning and Community Development 2016). These categories are; residential, commercial, office, mixed-use, industrial, open space, community facilities (fire stations, libraries, etc.), transportation, communications and utilities, and business park. When modeling out projected results for vegetated roof implementation, single-family residential, low-density residential, open space, and transportation, communications and utilities are all removed from the total area calculations. Both residential classifications consist of primarily detached homes, which usually have a roof slope too steep to support vegetated roofs, while open space, transportation, and communications and utilities are, for the most part, absent of buildings. While medium-density residential, high-density residential, and very high-density residential also include detached homes, they are included in total area calculations since the city classifies multi-family units, condominiums, and apartments within these subsets.

In the same comprehensive plan for the city, each zoning category is listed along with its respective percent coverage of city land. These percentages are multiplied with the total square

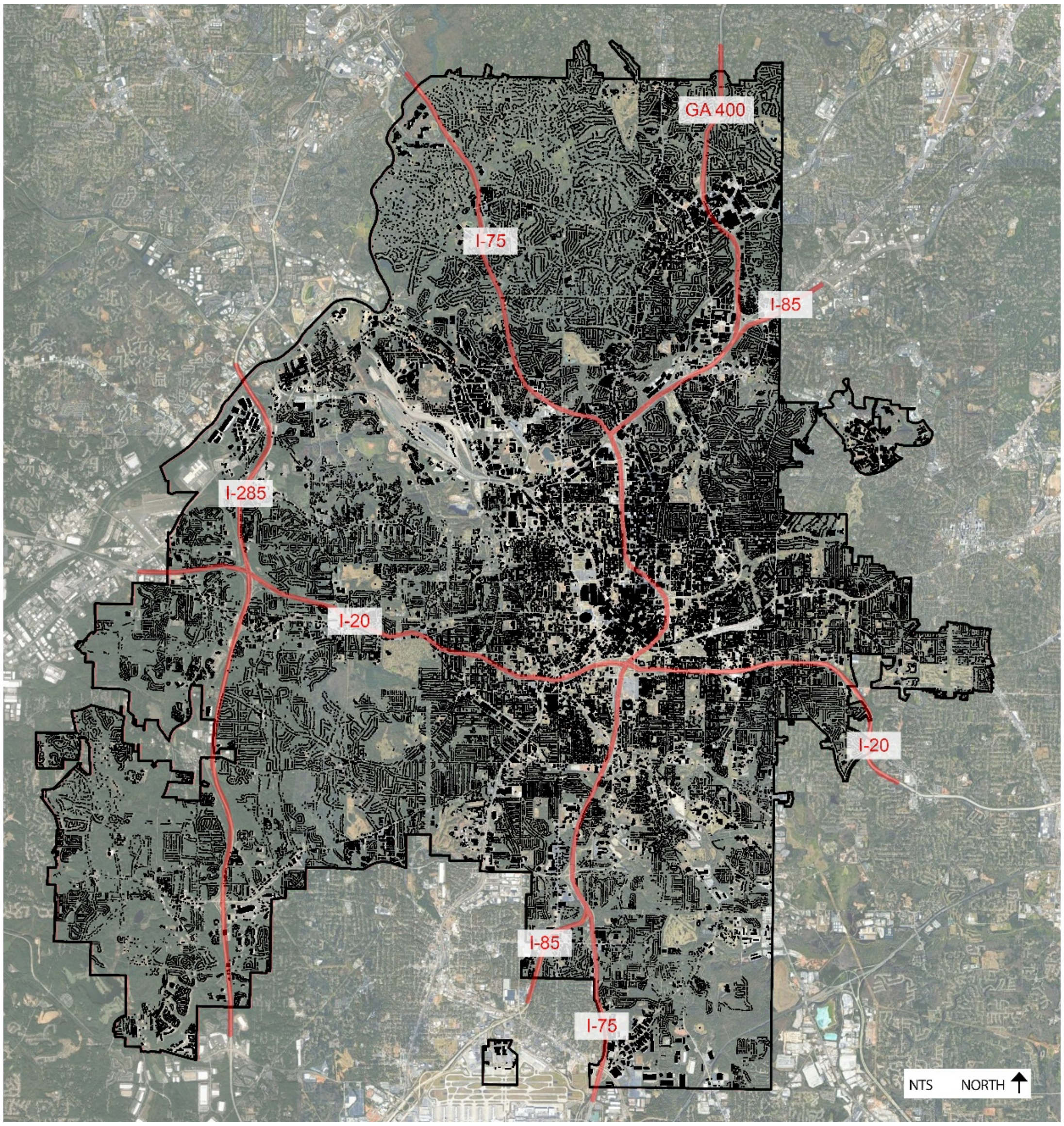

Figure 8: Building locations within the city of Atlanta in 2018.
Sources: (City of Atlanta 2018); (Google 2020b).

footage of rooftops found earlier in order to estimate each zoning type's available rooftops for vegetated roof development, as well as the total updated square footage of available rooftops in Atlanta.

From this point, different adoption rates are multiplied out using the data found from the individual vegetated roof in order to gain a better understanding of the cumulative ecosystem services which vegetated roofs can have on the city of Atlanta.

CHAPTER 4

RESULTS AND DISCUSSION

Precedent studies of vegetated roofs around the world help the reader visualize some of the projects previously discussed throughout this thesis, while also aiding to highlight the development gap which exists between Atlanta and other major world cities. Atlanta has ample available bare rooftops which, depending on structural capacity, could be retrofitted with similar styles of vegetated roofs examined. There is no one type of building which is able to support vegetated roofs. As long as the structure of the building is able to hold the added weight of vegetation, many of the following examples could translate to buildings within the city limits.

After the precedent studies, projective design takes site specific data and implements that into the previously highlighted formulas for energy reduction, air pollution, and stormwater runoff. The thesis can then extrapolate those results through different adoption rates across the city in order to calculate the ecosystem services and benefits vegetated roofs could have on the city as a whole.

Precedent Studies

This section is meant to be a resource guide about some interesting and groundbreaking projects within the field of vegetated roof design, while also allowing the reader to compare and contrast different development styles and techniques around the world. By examining projects from all around the globe and seeing how other cities are responding to urban climate issues through the use of vegetated roofs, a better view of Atlanta's vegetated roofs population and policy can be understood and critiqued. It is important that the selected projects vary in sizes, from the smallest at 2,000 SF (Southface Eco Office), to the largest at over 24 acres (Millennium Park). This allows the reader to see how different roofs bring different benefits and how vegetated roofs can be implemented on nearly every sized roof and are not limited to one size or roof shape. A majority of the sites selected are roughly the size of a typical building footprint (Toronto City Hall, Vancouver Convention Center, ACROS, Nanjing, Jacob K. Javits Center, High Museum of Art, Atlanta Botanical Gardens) and could easily be implemented anywhere around Atlanta. Sites such as the Ford's River Rouge Truck Plant or the Coastguard Headquarters are larger scale projects, but still could be implemented on buildings around the Atlanta area. With different distribution centers, corporate complexes, and manufacturing plants around the city, Atlanta is a good candidate for most any style and size of vegetated roof.

International

<u>Nathan Phillips Square Toronto City Hall Podium Roof</u>

Located in the heart of Toronto, this modular extensive vegetated roof, opened in 2010, covers close to 37,000 SF and had an initial cost was $2.3 million CAD. When originally constructed in the 1960s, the design of the podium level was for a raised public plaza; however, this was never completed. The vegetated roof brought life back to the plaza, providing height and texture on the large podium between City Hall. The space is Canada's largest publicly accessible vegetated roof, sees around 1.5 million visitors per year, provides views of downtown, and has walkways and furniture placed throughout. While the space provides benefits to the environment, it is often discussed most for the oasis that it provides in the heart of the city, especially as it provides a refuge to all who work and visit the political building which it surrounds. The space has won multiple awards, including the 2011 Canadian Society of Landscape Architects (CSLA) Regional Honour Award and the 2011 Green Roofs For Healthy Cities Award of Excellence in the Extensive Institutional category (Liveroof Ontario Inc. 2018).

Vancouver Convention Center

In 2009, the Vancouver Convention Center Expansion Project was completed and the center was opened. The project included an intensive vegetated roof which totals 261,360 SF in size. This roof is the largest vegetated roof in Canada and is home to over 400,000 different plants and grasses. The roof also hosts four different beehives, which supply honey for one of the building's kitchens while also helping to pollinate plants on the roof. The roof is not accessible to the public, however a pedestrian pathway cuts through a section of the vegetation and zig-zags up to a plaza space, allowing for close interaction with the plants. The roof helps to insulate the convention center in the summer and winter and has won multiple awards, including the 2010 Green Roofs for Healthy Cities Award of Excellence in the Extensive Institutional category, the 2013 AIA National Honor Award for Regional and Urban Planning, and the 2013 World Architecture News Sustainable Building of the Year Award (Greenroofs.com 2018d).

ACROS Fukuoka Prefectural International Hall

In the city of Fukuoka, in the southwest of Japan, lies a mountain of a building covered in vegetation. Constructed in 1994, architect Emilio Ambasz set out to create something unique. He stated that he wanted to replace 100% of the land that his building disturbed, while connecting the space to the existing adjacent park. He did not want typical low plantings that were usually found in urban areas, so his building design elevated the landscape almost 200 feet above street level through multiple terraces. The intensive vegetated roof's growing media ranges from 12-24 inches in depth, spans close to 106,000 SF, and is accessible to the public. The roof has lower temperatures than its surroundings, with a 2000 study finding a 15°C difference between the vegetation and adjacent concrete (Velazquez 2011). The building houses a symphony hall below the roof and multiple conference areas. It has won many awards, including the Business Week / Architectural Record Award in 2000 and First Prize in the Japan Institute of Architects Certificate of Environmental Architecture in 2001 (Ambasz and Greenroofs.com 2020).

Frankfurt International Airport

Just to the southwest of the city of Frankfurt lies one of the twenty largest airports in the world. The Frankfurt International Airport is one of the busiest in Europe, with over 70 million passengers annually. Being located in Germany, it is no surprise that the airport is home to multiple vegetated roofs. The first vegetated roof was constructed in 1990, and today the airport has over 20 vegetated roofs, both intensive and extensive, totaling over 500,000 SF. The largest of these roofs sits atop the Terminal 1 building and is approximately 180,000 SF in size (Velazquez 2018). While greening airport roofs is a new concept for the United States, many European airports have vegetated roofs onsite. One of the benefits to the Frankfurt airport's vegetated roofs is through noise reduction. A study found that they were able to minimize sound within the buildings by around five decibels (Dunnett and Kingsbury 2008).

Nanyang Technological University School of Art, Design and Media

The Nanyang Technological University School of Art, Design and Media sits just outside of Singapore and was constructed in 2006. The three boomerang shaped buildings intertwine with each other and are covered in intensive vegetated roofs totaling just over 107,000 SF. The buildings range from two to five stories, have roofs which slope upwards of 45 degrees, and are accessible to the public. The roofs help to keep energy use low and costs down, while also helping to lower the building's temperature. A smart irrigation system that uses recycled water from the building and can detect rainfall supplies the Zoysia and Ophiopogon grasses on the roof. The buildings have won the Green Mark Platinum Award for adopting best practices in environmental sustainability in 2011 (Greenroofs.com 2018c).

Domestic

Jacob K. Javits Center

The Javits Center in New York City is the busiest convention center in the United States, with an average of 2.5 million visitors per year. Located along the Hudson River between 34th and 40th streets, the center was renovated in 2014, when the extensive vegetated roof was installed. At 297,000 SF in size, the roof is the second largest vegetated roof on a free-standing building in the United States. The roof, designed for environmental purposes, contributes to lowered energy consumption for the building, cooler temperatures, and reduced stormwater runoff. The roof absorbs around seven million gallons (7 acre-feet) of water per year, which helps to reduce the amount of water in the city's sewer system and eases pollution within the Hudson River (Javits Center 2019). The building has already won several awards, even though expansion projects on the rooftops are still ongoing. One planned project is the addition of a rooftop farm, which will be one acre in size and is expected to produce 40,000 pounds of fruits and vegetables per year (Javits Center 2019). Along with the ecosystem services mentioned above, the vegetation helps to preserve the roof by protecting it from damaging UV radiation and provides a habitat for multiple species of birds, bats, and bees.

Chicago City Hall

As detailed in the policy section of this thesis, Chicago's history with vegetated roofs was kickstarted by the pilot project atop the City Hall building. Constructed in 2001, the semi-intensive vegetated roof is 20,300 SF and was installed at a cost of $2.5 million USD (which also included some structural repairs to the roof). The roof helps to save $5,000 USD per year in utility bills, can be as much as 30°F cooler than adjacent, non-vegetated roofs, and captures up to 75% of the rainwater which falls on the roof. The roof is home to 20,000 plants, provides beauty to those who work and live in the high-rises above, and won the Professional Merit Award in 2002 by the American Society of Landscape Architects (Greenroofs.com 2019a).

Millennium Park

One of the most recognizable vegetated roofs in the world lies in the heart of Chicago. Millennium Park, an over-structure vegetated roof, sits atop multiple parking garages and a commuter rail line. The park, which is over 1 million SF (24.5 acres), opened in 2004 and is considered a large success. It was constructed at a cost of around $500 million USD that came from both private and public funding. It is hard to imagine that, in the late 1990s and early 2000s, the site was a ground-level parking lot and a rail yard given its location within the city. The park is famous for its multiple attractions, including Cloud Gate (The Bean), the Crown Fountain, Jay Pritzker Pavilion (the amphitheater), and the Lurie Garden. The Lurie Garden alone has upwards of 26,000 plants and cost over $13 million USD (Freeman 2004). Among every type of ecosystem service imaginable, the park helps to boost the tourism industry of Chicago. It is estimated that some 25 million visitors can pass through the park per year and the city has added 15,000 to 20,000 hospitality jobs due to the park's presence (Tafoya and Torres 2017). The park has won numerous awards, including the 2005 Green Roofs for Healthy Cities Award of Excellence in the Intensive Industrial/Commercial category (Greenroofs.com 2019b).

Ford Motor Company's River Rouge Truck Plant

One of the most famous vegetated roofs in the United States sits atop Ford's Dearborn Truck Plant just outside of Detroit. When the building was renovated in 2003, an extensive 454,000 SF vegetated roof was added, making it the largest vegetated roof in the United States and one of the top five largest in the world. Sedums and other succulents installed with the Xero Flor Green Roof System cover the roof. This system, originally engineered in Germany, is pre-vegetated with only 1.25 inches of growing medium and is very lightweight. Due to it being pre-vegetated, the roof was able to achieve over 90% coverage upon installation and because of the thin growing medium, it is difficult for weeds to grow which makes maintenance on the system much easier. The roof can hold up to an inch of rainfall, absorbs local carbon dioxide, reduces greenhouse gases, and keeps the building warmer in winter and cooler in summer. In 2004, the roof was recognized by the Guinness Book of World Records as the largest living roof, and also received the 2004 Award of Excellence in the Extensive Industrial Commercial category from Green Roof for Healthy Cities (Greenroofs.com 2018a).

Douglas A. Munro Coast Guard Headquarters Building

When the United States Coast Guard decided to consolidate their headquarters into one campus, they chose to move to a 176-acre site which had previously housed a government-run hospital that opened in 1855. The site was renovated and opened in 2013, and currently houses over 40 buildings on 11 different levels which are stepped into the existing hillsides. The vegetated roofs are located on top of 18 of the buildings, as well as nine courtyards, and two parking garages. The roofs are made up of both extensive and intensive systems and provide over 550,000 SF of coverage. They were installed for stormwater management and energy efficiency purposes and, together with other amenities onsite, help to reduce stormwater runoff by 47% (U.S. General Services Administration 2011a). The project has won many awards, including the Award of Excellence, Best Sustainable Project from NAIOP MD/DC Chapter, the WBC Craftsmanship Award – Special Construction, Green Roof, and the WBC Craftsmanship Award – Landscaping (Skopic 2020).

Atlanta

City Hall

Much like the examples from Toronto and Chicago, Atlanta intended to kickstart its vegetated roof culture with a pilot program at City Hall. Located at 55 Trinity Ave. SW, the semi-intensive roof is on the fifth floor, accessible to workers and visitors, and is 3,100 SF (of which 1,000 SF are pavers). The roof was constructed in 2003 and is visible from the surrounding buildings, offering views to those who work above. The plants are low, mainly sedums and perennials, and the roof was constructed without irrigation. Unlike previous examples from other cities, this project did not thrive and had to go through renovation in 2017 at a cost of $135,000 USD. The renovation was required as the roof was falling into disrepair due to a lack of maintenance. The cost that went into renovation provided for more seating and to remove invasive weeds (Pendered 2017). As of writing, there is no new information on the roof and time will tell if it can attract more attention to begin a culture of vegetated roofs within the city of Atlanta.

Frances Bunzl Administration Center of the High Museum of Art

The High Museum of Art is an icon within the city of Atlanta and showcases some of the latest in art, design, and technology through its exhibits. Because of this, it is no surprise that cutting-edge technology was expanded outside in the form of a modular extensive vegetated roof. Sitting atop the administration center, the roof is located at 1280 Peachtree St. NE. Completed in 2008, it is the largest modular system in the city at 6,680 SF in size. The roof was constructed to help reduce water runoff, lower UHI, improve air quality, and extend the life of the roof. It has the ability to capture over 60,000 gallons (0.18 acre-feet) of stormwater a year, which is around 70% of the total received for the roof (Greenroofs.com 2018b) .

Atlanta Botanical Garden Hardin Visitors Center

The Atlanta Botanical Garden first opened in 1976 and is located in the heart of midtown Atlanta at 1345 Piedmont Ave. NE. The garden provides 30 acres of formal, natural, and exotic plants, and, since 2010, three vegetated roofs. When the garden went through a partial addition and renovation, new vegetated roofs were three items they wanted to add. Located at the Hardin Visitors Center, two extensive roofs and one intensive roof were added for a combined total of 4,500 SF (Higgins and Greenroofs.com 2018). Only the intensive roof is accessible to the public, while the two extensive roofs can be viewed from inside the Visitor's Center. The three roofs are planted with trees, shrubs, perennials and sedums and were implemented to lower temperatures, provide sound insulation, and new habitats for wildlife and visitors to explore.

Ponce City Market

When Ponce City Market was renovated and reopened in 2014, many sustainability measures were taken. One of the benefits of the renovation was the addition of the vegetated roof above the entrance which faces North Ave. The 14,000 SF extensive sedum roof aids in stormwater runoff, keeping the UHI low, and insulates the building during the summer and winter which is an added bonus for residents and workers above. The roof can be located at 675 Ponce De Leon Ave. NE and provides a nice view throughout the day.

Southface Eco Office

Located at 241 Pine Street NE, Southface is known for being a non-profit leader in promoting sustainable living. When they built their eco office in 2009, one of the features was the 2,000 SF extensive vegetated roof placed on top. The roof helps to mitigate the UHI, cools the office, and works to capture stormwater runoff. The office has won many awards, including the Urban Land Institute's Development of Excellence Award in 2010 (Nicolow and Velazquez 2018).

Reflections on Precedent Studies

One of the difficult aspects of this section was the initial project selection. Many different criteria could have been followed, including award winning designs, only modular, extensive, intensive, retrofits, or new builds. The list for possible precedents in their relation to implementation in Atlanta could include hundreds, if not thousands, of roofs and could be the subject for further study. For each category; international, domestic, and Atlanta, one goal was to select at least some projects mentioned before in this thesis so that the reader is able to better understand those specific projects or to see how they may have been/are being a catalyst for a paradigm shift within their geographical areas. Another main goal of precedent selection was to find some projects which closely relate to, or could be constructed on, existing buildings in Atlanta (Frankfurt International Airport, Vancouver Convention Center).

By researching test projects from Toronto or Chicago earlier in this thesis and identifying how they helped to kickstart policy change within their cities, and then detailing them further in this section, it is the hope that some parallels could be drawn to Atlanta. As seen in the coming pages, Atlanta's current vegetated roof development is far behind those of Chicago, Portland, New York City, or Washington, D.C. Through highlighting the two city hall pilot projects, as well as the vegetated roof on Atlanta's city hall, this thesis can highlight some of the comparisons and gaps found between related projects.

International

Nathan Phillips Square helped kickstart Toronto's vegetated roof growth. The project opened up right when the city passed its Green Roof Bylaw, which was the first of its kind in North America to require the construction of vegetated roofs. Until the opening of the vegetated roof, Toronto's city hall podium roof had been inaccessible to visitors. Following the opening, the space grew in popularity and became a bright spot to the city and an example of how vegetated roofs could transform the existing urban rooftop.

I chose the Vancouver Convention Center partially due to personal reasons. Having visited the city of Vancouver multiple times, I have been able to see first-hand the spectacle of the Convention Center vegetated roof. It is every bit as beautiful in person as it looks in photographs, and the way in which the architects have been able to make the entire building eco-friendly is inspiring for urban buildings of the future. The project also highlights the fact that a vegetated roof can create a great tourist opportunity for both building and city, while also serving its main environmental and economic purposes.

As mentioned previously, Germany is one of, if not, the most influential countries in vegetated roof development. While there are many projects to choose from within the country, the Frankfurt Airport seemed the best choice due to its specific site. Airports all around the world are home to some of the largest buildings and fewest trees. Those, combined with the amount of impervious paving for runways and taxiways, make them not very environmentally friendly. By utilizing the existing rooftops for stormwater retention, air pollution mitigation, and sound insulation, vegetated roofs could quickly take over and instantly make great impacts. Due to Atlanta having the busiest airport in the world, the city could also utilize vegetated roofs as a marketing for green infrastructure throughout the city.

Since Canada and Germany had been highlighted with projects, geographically Asia was selected in order to spread out the different studies. The ACROS International Hall and the Nanyang Technological University are both located in regions and cultures where vegetated roof development is expanding, and both have been featured many times in both architectural and landscape publications. One feature that both of these projects share is the ability for the visitor to interact with the vegetated roof through walkways which are part of the designs. While City Hall in Toronto and the Vancouver Convention Center also allow for visitors to interact with the roofs, both roofs in Asia incorporate the visitor into the entire experience of the roof. Both roofs are multi-leveled and give pedestrians an opportunity to climb up onto the roofs and “into” the vegetation. One of the most challenging obstacles of vegetated roof development is the economics. By allowing visitors to access the roof, designing that access in an architectural way, and incorporating it into the final layout, there could be a better chance to change public opinion on vegetated roofs, generate more demand, and generate more funding/grants through new policy.

As mentioned, these two roofs allow the visitor to immerse themselves in the roof more so than a standard, flat vegetated roof on the top floor of an office building. The experience of climbing up the vegetated roof and “into” the design is different to most every other vegetated roof. One important question that developers, designers, and clients will need to start asking is what the future of commercial office space will look like, especially after the coronavirus pandemic. Will Atlanta continue to see its urban workforce occupy high-rise buildings along the interstate corridors, will the majority of workers be remote, or will cultural change lead to companies renting more communal style office spaces in larger buildings along the beltline or similar pedestrian hotspots, such as Ponce City Market or Krog Street Market in Atlanta? If the latter was to be the case, office buildings may have a much larger footprints and vegetated roofs would be perfect for adorning these spaces, bringing economic, environmental, and social benefits.

Not only will commercial office space need to be evaluated, but also schools and universities. Will there be a full return to in-person teaching once the pandemic is over, or will a hybrid method come out of this experience, leaving some existing buildings unused? If that were to be the case, these buildings would need to be repurposed. Could the rooftop play a role in that repurposing?

According to one report, almost twice as many workers are now working remotely due to the coronavirus pandemic (Stanford University 2020). When the pandemic is over, much thought will need to be given to what the workplace will look like. If companies survive six months to a year by working remotely, will they want to go back in-person and pay rent in an urban commercial building? One survey shows that there is a drop in high-rise office demand among employees at the rate of 25% (Stanford University 2020). The same study seems to believe that when it may be safe to go back to work, there could be a rise in office space in the suburbs due to lower costs and a lower workforce.

With all these factors playing against commercial office space in urban areas, thought will have to be given to what possible amenities developers could offer potential tenants. Vegetated roofs, similar to those of ACROS or Nanyang could be an option. Rooftops which incorporate urban farming, employee greenspace, or wildlife habitats could be a draw for some companies. With the environmental benefits that vegetated roofs provide and the social features they have the potential to bring, they could be a very real option for helping the workforce return to the office after the pandemic.

Domestic

Looking at domestic projects, the Jacob K. Javits Center is a fantastic example of an urban vegetated roof. Similar to the rooftop in Vancouver in that they both are situated on top of convention centers, the Javits Center can be a model for a large-scale developed roof. With the addition of the one-acre farm in the near future, the roof will help to serve as the largest rooftop farm in Manhattan (Javits Center 2019). That, in addition to its ability to offset a large amount of carbon, retain and remove stormwater from the city sewers, and its housing of local wildlife and honey bees, helps to show that vegetated roofs can provide a wide variety of services to both the local environment and social constructs of an urban area. By taking rough area calculations via Google Earth, it appears that anecdotally there are three Javits Centers compared to one Georgia World Congress Center (GWCC). By just adding a similar vegetated roof on top of the GWCC, Atlanta could be able to make an immediate impact to the environment as well as provide social benefits, learning opportunities, or urban farming to the local community.

One of the most famous vegetated roofs within the United States' green infrastructure community would have to be the Chicago City Hall. Implemented in 2001 as a pilot project, the roof was constructed in order to determine what the impact of vegetated roofs within the Chicago community could be. Because of these, I included this project in the precedent study. Since the roof was implemented, the city has seen a large growth in vegetated roof development, is continually one of the top cities in terms of implementation per year, and saw almost 500,000 SF of vegetated roofs implemented in 2018 alone (Stand and Peck 2019). This project, as well as the Toronto City Hall vegetated roof, can serve as an inspiration for Atlanta in terms of using public or government buildings in order to kickstart a vegetate roof movement. By using public space, and leading by example with green infrastructure, Atlanta could see a drastic change in vegetated roof implementation.

Perhaps one of the most famous vegetated roofs in the world is Millennium Park in downtown Chicago. While most people may not think of that space as a vegetated roof, it sits above a parking garage in the middle of the city. I selected this project to illustrate an example of a vegetated roof that does not fit the same standards that one may think of when they imagine vegetated rooftops. Vegetated roofs do not necessarily have to be placed on the tops of buildings, and they can most certainly be used for widescale recreation, which then could raise awareness of their uses and possibilities within the community.

The Ford Motor Company's Truck Plant roof was selected mainly for its popularity. One of the largest and most popular vegetated roofs in the world, the roof was specially designed to be as lightweight as possible, given the roof is over a manufacturing plant and has larger spans than typical commercial roofs. The system has held up well over time and weighs only 10 lbs/SF when saturated (Greenroofs.com 2018a).

Lastly, I selected the Coast Guard Headquarters Building in Washington, D.C. due to its history and impressive design. Having been the site of a hospital in the 1800s and 1900s, the site was renovated into the campus that it is today. With over 40 buildings, a large green infrastructure pledge was made on the site to incorporate vegetated roofs to the best of possibilities on many of the buildings. Totaling over 500,000 SF, the roofs are a good precedent for any corporate campuses or university campuses looking to upgrade their green infrastructure plans or overall designs. Atlanta has many opportunities for such spaces, such as the multiple movie studios in and around the area, corporate campuses in the downtown corridor, news stations, college buildings, or even self-storage buildings which have multiple rowhouse style buildings.

Atlanta

Precedent studies within Atlanta were more difficult to research due to the lack of information online. Some websites list different projects within the city, however some of those projects are either no longer in existence or have been so poorly maintained that they are not worth highlighting. Whether this is due to improper maintenance, drought, plant material failure, or another cause is not immediately known and could be the subject of future study. As Atlanta is further south than all but one or two of the precedent studies, the climate could affect maintenance practices of vegetated roofs. What works in Chicago, Toronto, or Germany as far as irrigation and plant material may not work in Atlanta. This is where proper education surrounding vegetated roofs comes into play. If Atlanta is going to one day develop more vegetated roofs, contractors, developers, and designers need to be more educated on what it takes for the roof's ultimate survival.

I selected the City Hall project due to its correlation to the similar projects in Toronto and Chicago. The roof is a decent enough size that should yield environmental benefits, but has already once fallen into disrepair once and needed renovation. Now, 17 years after opening, it sits as purely an example of a vegetated roof, and not as a precedent for mass implementation around the city.

The Atlanta Botanical Garden, and any other botanical garden in the world, should be a great candidate for vegetated roof implementation. It is the perfect setting for plant trials, design, and research. Further, it could serve as a learning area for visitors to the garden, helping to raise awareness on the power of vegetated roofs. Instead, the garden has a small plaque erected to explain that it is a vegetated roof, but the area is nothing special. Raised beds sit along a walkway which one can take a quick tour of the space, but the roof is so small that it takes no time at all. The area feels no different than many other areas in the garden and does not do much to sell the idea of implementation throughout the city. I attempted to contact the Atlanta Botanical Garden to discuss their vegetated roofs and the benefits that they see through their existence, but no answers were ever received.

Ponce City Market is a great candidate for vegetated roofs in Atlanta. Originally built as a retail store and distribution warehouse for Sears, Roebuck & Co. in the 1920s (Ponce City Market 2020), today the building is home to offices, residential units, shops, restaurants, and entertainment. Located along the Atlanta Beltline, the building has become very popular since being renovated and reopened in 2012. The building currently has an extensive vegetated roof above one of its entrances, however there is very little information or marketing available about its capabilities and ecosystem services. The website for the building markets the roof, and it even has its own dedicated website, however this is the top floor of the main area in the building where people can go to eat, drink, play games, and socialize among limited plantings. The rest of the building has close to 50,000 SF of available planting areas for vegetation, if not more. Due to the social popularity of Ponce City Market, as well as its prominence along the Beltline, if its existing vegetated roof were marketed better or more were added to available areas, the building could be a great example for the rest of the city and could have the potential to help kickstart the implementation of vegetated roofs in Atlanta.

After conducting research on these precedent studies and reflecting on their functions, sizes, and impact to their surrounding regions, it is even more apparent that Atlanta is far behind on the development of vegetated roofs. While precedent studies in other cities provide multiple details and benefits on the performance and ecosystem services of their rooftops, very little information can be found about those in Atlanta. Some vegetated roofs in Atlanta have almost no information or data connected to them, with websites of the owner or architect barely mentioning the existence of the roof. Other Atlanta vegetated roofs which were initially thought of for research in this section appeared to either no longer be on the building or neglected to the point where most of the vegetation is gone. Whether this is due to a lack of desire for vegetating the rooftops, a lack of knowledge, or another reason is yet to be known. If Atlanta wants to further improve its environment, a paradigm shift is needed concerning the rooftops.

Projective Design

Now that this thesis has taken a review of precedent studies from both around the world and around Atlanta, focus is shifted to projective design. Vegetated roofs can have great individual site benefits and provide ecosystem services to the larger urban areas where they are implemented. They have served as a catalyst and kickstarted other projects, been a tool to influence policy, and been recognized by many disciplines for their impacts to urban areas. This section takes a deeper dive into their individual benefits by modeling out an example 20,000 SF vegetated rooftop in Atlanta.

In order to gain better knowledge about site benefits, some context of climate and existing conditions need to be inferred. Atlanta has a temperate humid subtropical climate, with summer temperatures in ranging between 70-90°F average and winter temperatures averaging between 35-60°F. Earlier, research into canopy coverage showed that close to half of city land was covered in urban tree canopy. This shows that, although Atlanta is richly covered in canopy and is known as the city in the forest, there are still many areas of the city without vegetation and with large amounts of impervious cover. The coverage statistics also helped to identify areas within the city which are in more need of vegetated coverage, such as commercial, industrial, and multi-family land, as well as denser urban areas such as downtown, midtown, or Buckhead.

Sample Roof Calculations

This thesis will examine first the benefits of a singular vegetated roof and then extrapolate results into different adoption rates throughout the city. This singular modeled roof is assumed to be a 4” extensive roof, 20,000 SF in size (80% of a typical office floorplate of 25,000 SF). This assumption and method of calculation will serve as the base for the following benefit calculations.

Energy Savings

In discussing the many benefits of vegetated roofs, one of the most prominent is their ability to provide energy savings to buildings. Whereas trees are able to shade the sides of buildings if close enough, vegetated roofs aid in stopping heat loss in the winter and cooling loss in the summer, providing better thermal comfort inside. By calculating CDD (2,645) and HDD (2,117) for Atlanta, annual heating and cooling savings for a 20,000 SF vegetated roof can be calculated using equations (1) and (2) laid out in the methods section:

CDD=

$$2{,}645°F * 24\ hrs * \left(\frac{Btu}{11.34\ SF * °F * hrs}\right) - \left(\frac{Btu}{23.4\ SF * °F * hrs}\right)$$

$$63{,}480°F\ hrs * \left(\frac{Btu}{11.34\ SF * °F * hrs}\right) - \left(\frac{Btu}{23.4\ SF * °F * hrs}\right)$$

$$\left(\frac{63{,}480\ Btu}{11.34\ SF}\right) - \left(\frac{63{,}480\ Btu}{23.4\ SF}\right)$$

$$5{,}597.88\frac{Btu}{SF} - 2{,}712.82\frac{Btu}{SF}$$

$$2{,}885.06\frac{Btu}{SF}$$

There are 3,412 Btu in 1 kWh, so in order to convert the final energy savings, 2,885.06 is multiplied by 1/3,412:

$$2{,}885.06 * \frac{1}{3{,}412} = .8455\frac{kWh}{SF}$$

$$.8455\frac{kWh}{SF} * 20{,}000\ SF = 16{,}910\ kWh\ in\ annual\ cooling\ savings$$

HDD=

$$2{,}117°F * 24\ hrs * \left(\frac{Btu}{11.34\ SF * °F * hrs}\right) - \left(\frac{Btu}{23.4\ SF * °F * hrs}\right)$$

$$50{,}808°F\ hrs * \left(\frac{Btu}{11.34\ SF * °F * hrs}\right) - \left(\frac{Btu}{23.4\ SF * °F * hrs}\right)$$

$$\left(\frac{50{,}808\ Btu}{11.34\ SF}\right) - \left(\frac{50{,}808\ Btu}{23.4\ SF}\right)$$

$$4{,}480.42\frac{Btu}{SF} - 2{,}171.28\frac{Btu}{SF}$$

$$2{,}309.14\frac{Btu}{SF}$$

$$2{,}309.14\frac{Btu}{SF} * 20{,}000\ SF = 46{,}182{,}800\ Btu\ in\ heat\ savings$$

In Atlanta, the current electricity rate for commercial properties is $.0929 (Electricity Local 2020). Multiplied out by CDD savings gives a total annual cooling cost savings of $1,570.94 for the 20,000 SF vegetated roof. In June 2020, Georgia had an average commercial cost of $.00000808/Btu (U.S. Energy Information Administration 2020). If multiplied together, yearly natural gas savings from the 20,000 SF roof in Atlanta would be $373.15. Combined with electricity savings, the 20,000 SF roof with 4" of growing media could see an annual heating/electricity savings of $1,944.09. If this roof were to last similar to some German rooftops who have an average lifespan of 90 years, energy savings alone for the lifetime of the roof could be just shy of $175,000. By comparison, the USDA Forest Service estimates that a red maple in the Piedmont region of the United States will, over the course of 40 years, provide 89 kWh/year in cooling savings and 415k Btu/year in heat savings (McPherson et al. 2006). Based on the prices above, savings per year would be $3.35 in heating and $8.27 in cooling, for a total of $11.62 per year and $464.80 over the forty-year period. Per these numbers, 168 red maples would needed in order to equal the same amount of energy savings as the 20,000 SF vegetated roof.

With the combined heating and cooling savings, the 20,000 SF roof will account for a reduction of 30,445 kWh annually. According to the EPA, this is the equivalent in greenhouse gases of keeping 4.7 passenger cars off the road, the CO_2 equivalent of over 2,400 gallons of gas consumed, and the sequestration rate of 28.1 acres of forests (U.S. Environmental Protection Agency 2018a). While the estimated heating and cooling savings numbers above are based on the most current data for Atlanta in terms of HDD, CDD, natural gas prices, and commercial electricity prices, many different local factors can impact actual savings. These can include; the soil depth and composition, plant selections, building location, and climate (Center for Neighborhood Technology 2011).

Air Pollution

Air pollution is one of the most dangerous aspects of urban living. With urban populations growing, combined with a rising climate, the risk of disease, ailment, or death due to air pollution is also likely to increase. Through the use of green infrastructure, especially vegetated roofs, air pollution can be combatted in order to make cities more pleasant to live in. With so many existing rooftops, this opportunity is all around urban areas.

By following the range of air pollution values found by Currie and Bass (2008) and Yang, Yu, and Gong (2008), expected annual air pollutant removal for a 20,000 SF vegetated roof is as follows:

O_3 –5.340-10.800 kg

NO_2 –2.720-5.460 kg

SO_2 –1.200-3.680 kg

PM_{10} –1.040-2.820 kg

The USDA Forest Service provides expected pollutant removal for different sized trees. In their report, a red maple is able to remove an average of .186 kg of NO_2, .095 kg of O_3, .372 kg of SO_2, and .141 kg of PM_{10} annually over a 40-year span. The total air pollutants removed by that one red maple over the 40-year span would be 31.751 kg, whereas the total air pollutants removed by the 20,000 SF vegetated roof during that same time could be between 412-910.4 kg. With this, 13-29 red maples would equal the air pollutant removal of the vegetated roof.

When examining the air pollutant removal by vegetated roofs, it is also possible to calculate expected pollutants avoided through energy reductions. This is more of a secondary benefit to adjacent rooftops and uses, but could still positively affect the building's rooftop. Using the annual heating and cooling savings and multiplying these by the EPA's emission rates for the state of Georgia identified in the methods section, air pollutants avoided through energy savings can be calculated. When multiplied by the annual electricity savings of 16,910 kWh, the vegetated roof will save the following annually:

CO_2 – .420 kg/kWh * 16,910 kWh = 7,102 kg avoided through reduced cooling needs

CH_4 – .000036 kg/kWh * 16,910 kWh = .608 kg avoided through reduced cooling needs

N_2O – .0000054 kg/kWh * 16,910 kWh = .0913 kg avoided through reduced cooling needs

NO_x – .000181 kg/kWh * 16,910 kWh = 3.061 kg avoided through reduced cooling needs

SO_2 – .000136 kg/kWh * 16,910 kWh = 2.300 kg avoided through reduced cooling needs

Heat savings calculated earlier show the vegetated roof could save 46,182,800 Btu (46.1828 MMBtu), which avoids the following pollutant numbers:

CO_2 – 69.832 kg/MMBtu * 46.1828 MMBtu = 3,225.04 kg avoided through reduced heating

CH_4 – .00589 kg/MMBtu * 46.1828 MMBtu = .272 kg avoided through reduced heating

N_2O – .00091 kg/MMBtu * 46.1828 MMBtu = .042 kg avoided through reduced heating

NO_x – .0336 kg/MMBtu * 46.1828 MMBtu = 1.552 kg avoided through reduced heating

SO_2 – .0231 kg/MMBtu * 46.1828 MMBtu = 1.067 kg avoided through reduced heating

Lastly, in determining the amount of CO_2 removed through the sequestration of C, the size of the vegetated roof is multiplied by the average of .01533 kg/SF of sequestration, which yields 306.6 kg annually sequestered. This is converted to CO_2 by multiplying C by 3.67, which gives a result of 1,125.22 kg of CO_2.

All reductions are added together in order to determine the total removed and avoided air pollutants by a 20,000 SF extensive vegetated roof in Atlanta (Table 5). Also calculated is the estimated economic value of air pollution removal and avoidance as identified in the methods section. This value finds that the 20,000 SF vegetated roof can provide between $400.40-1,326.64 USD annually in benefits.

Table 5: Air pollution removal rates of a 20,000 SF extensive vegetated roof in Atlanta

Air pollution removal rates of a 20,000 sf extensive vegetated roof in Atlanta, GA							
	Pollution Removal by Plant Material (kg)	Pollution Avoided through Reduced Cooling (kg)	Pollution Avoided through Reduced Heating (kg)	Carbon Sequestration by Plant Material (kg)	Total Pollutants Removed	Value of Pollutant Removal ($/kg)	Total Air Pollution Benefit ($USD)
CO_2		7,102	3,225.04	1,125.22	11,452.26	.0167-.085	191.25-973.44
CH_4		0.608	0.272		0.88	.41-2.20	.36-1.94
N_2O		0.0913	0.042		0.133	3.86-31.97	.51-4.25
NO_x	2.72-5.46	3.061	1.552		7.33-10.07	14.44	105.84-145.41
SO_2	1.2-3.68	2.3	1.067		4.57-7.05	4.21	19.24-29.68
O_3	5.34-10.8				5.34-10.8	14.59	77.91-157.57
PM_{10}	1.040-2.82				1.040-2.82	5.09	5.29-14.35
						Total ($USD)	**400.40-1,326.64**

Overall, savings from captured and sequestered carbon account for the greatest value while reductions in CH_4 account for the least. These removal rates and cost savings can be multiplied out on different adoption rates in order to determine total economic benefits for Atlanta due to air pollution removal rates.

Stormwater Reductions

Perhaps one of the strongest arguments for the inclusion of vegetated roofs is their ability to retain and reduce stormwater runoff from urban sewer systems. Helping to limit the occurrence of sewer overflows and eliminating pollutants from water systems are two of the major advantages of vegetated roofs when it comes to stormwater management. While the goal of conventional roofs is to channel water into drains and off site as quickly as possible, vegetated roofs allow for water to be held in the substrate to either be used by plants and evapotranspired back into the atmosphere, or they will delay the runoff time into sewers and ease the initial shock that a rainstorm may cause to urban infrastructures.

From equation (5) identified in the methods section, the annual precipitation for Atlanta is plugged in with the roof area and retention rate in order to determine the annual stormwater reduction.

$$annual\ precipitation\ * roof\ area\ (SF) * retention\ rate\ (\%) * 144 \frac{inches}{SF} * \ .0043 \frac{inches}{cubic\ foot}$$

$$49.17 * 20{,}000 * .65 * 144 * \ .0043 =$$

$$395{,}798\ gallons\ (1.21\ acre\ feet)\ reduced\ annually$$

By comparison, the USDA Forest Service estimates that a red maple is able to intercept 4,778 gallons per year average over a 40-year period (McPherson et al. 2006). During that 40 years, the red maple would intercept 191,120 gallons (0.58-acre-feet) and the vegetated roof could intercept 15,831,920. 83 red maples are needed to equal the interception capabilities of the 20,000 SF vegetated roof.

From the avoided stormwater treatment cost of $29.94/acre-feet identified by the CNT, the 20,000 SF vegetated roof could provide $36.36 in annual savings of avoided water treatment costs. If the 20,000 SF vegetated roof were intensive and assumed an 85% retention rate, following the same formulas above could see 517,583 gallons (1.58-acre-feet) of stormwater retained at a savings of $47.55 in treatment. If a modular system were used, or an extensive system with a shallower substrate and only 45% retention were possible with the vegetated roof, those numbers could be 274,014 gallons (0.84-acre-feet) and a benefit of $25.17 in treatment costs.

Schematic Design Options of the 20,000 SF Sample Roof

Two schematic designs for a 20,000 SF office building are included for visual reference of possibilities of vegetated roof designhelp gain a better visualization of the methods, calculations, and ideas presented in this thesis. One roof is based on a potential new construction vegetated roof (Figure 9), where the building utilities and HVAC can be located closer to the perimeter of the building edge for easier maintenance access. Also shown in the plan is a walkway around three edges of the roof for access to vegetation or where other utilities, such as hose bib connections for temporary irrigation, can be located. The roof assumes a simpler organic design with fewer planting beds and larger swaths of each plant. The other roof re-imagines an existing roof in the Buckhead area of Atlanta located along Lenox Road NE across from Lenox Square Mall (Figure 10). Since this is an existing building, the roof is designed around the current utilities/HVAC units in the center of the roof and shows an alternate to the previous plan for a more complex, geometric design. The roof provides a stone edge between the building perimeter wall and vegetation, which could serve as maintenance access or for the location of any necessary hose bibs. A walk is also provided from the existing utilities to the perimeter of the design for access to the building perimeter wall.

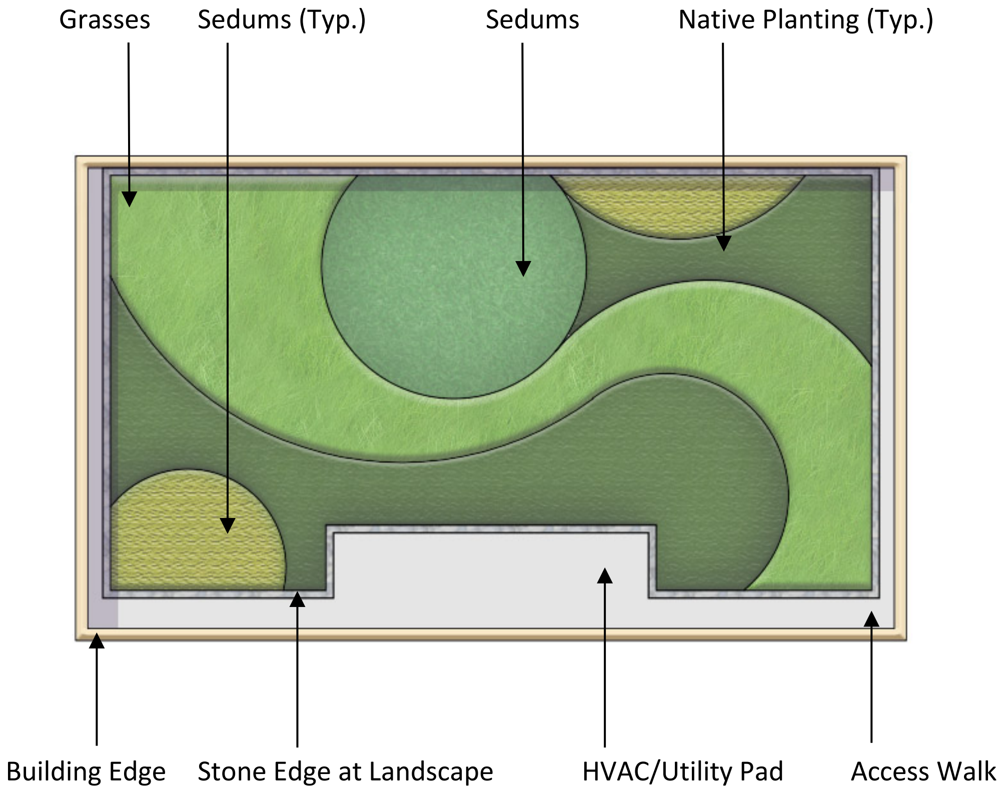

Figure 9: Sample schematic design of a 20,000-SF extensive vegetated roof.

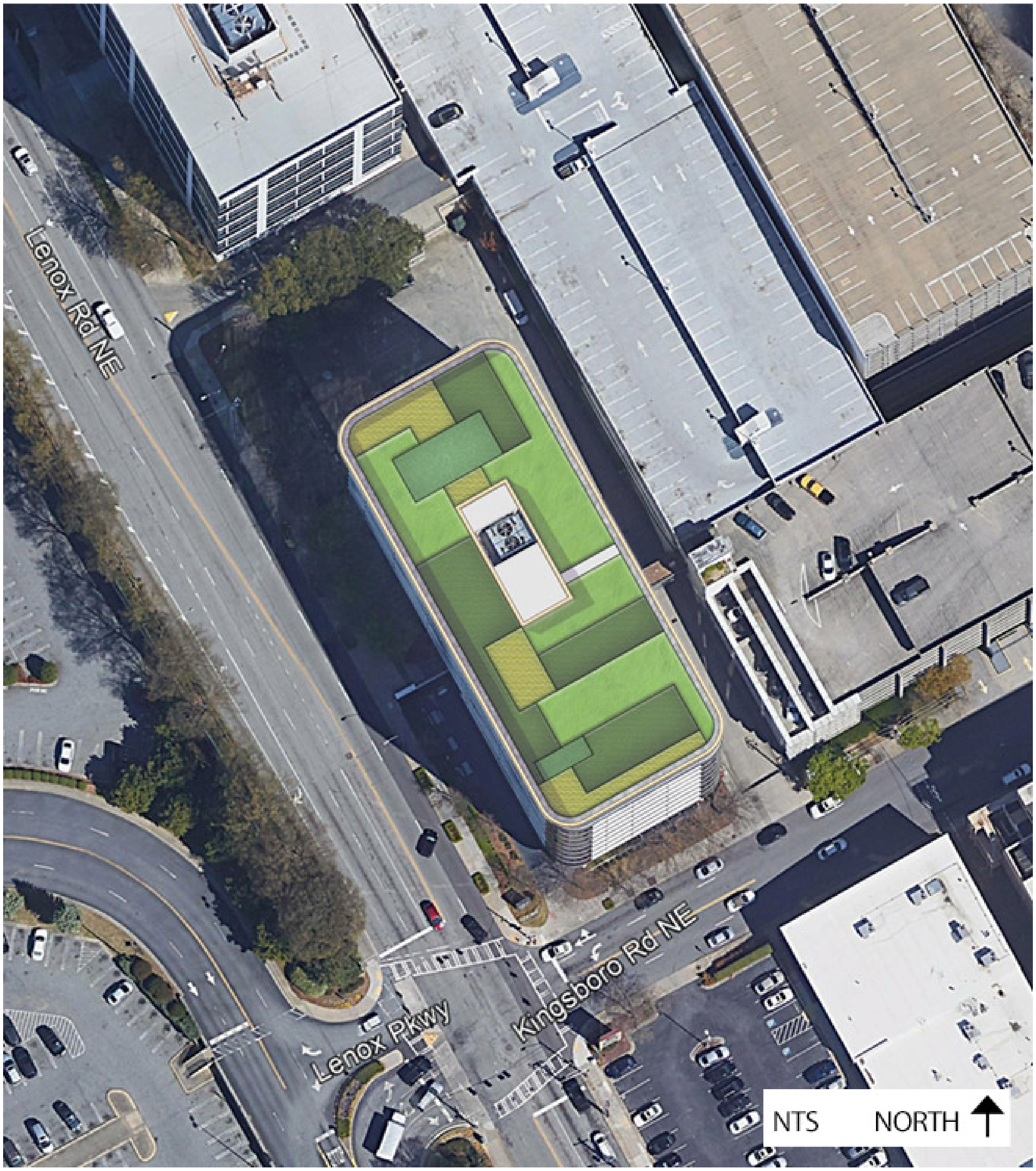

Figure 10: Sample schematic design of an extensive vegetated roof on an existing building in Buckhead.
Source: (Google 2020a)

Scaled Calculations and Adoption Rates

In order to better determine more overall benefits to the city of Atlanta, the results from the 20,000 SF roof are extrapolated in different adoption rates to better answer the second question of the thesis. Earlier, this thesis looked at vegetation coverage in the city of Atlanta (Figure 6). This graphic helps to visualize the total coverage of the city's vegetation, both past and present. By highlighting the negative space from that image, it is possible to visualize the areas of Atlanta not covered in vegetation (Figure 11). These areas are important as they help to illustrate the areas of the city most in need of vegetated coverage, either by tree or vegetated roof. By overlaying this image in photoshop with the map of existing buildings within the city, it is possible to gain an understanding of the extent of buildings within the non-vegetation areas of Atlanta (either the buildings are lower without surrounding tree canopy or taller and extend above the canopy) (Figure 12). All areas in red represent rooftops located within these areas of non-vegetation in the city.

By taking the total building coverage for the city of Atlanta, gathered through the Department of Planning's website, and multiplying it by the percentage of different land use categories identified by Atlanta's 2016 Comprehensive Development Plan, the total square footage of possible vegetated roofs can be inferred (Table 6). Through these calculations, there are now 131,136,123 SF of available rooftops for vegetated roof implementation. The remaining 66% of rooftops are found in the single-family residential, low-density residential, open space, and transportation, communication and utilities zoning categories, which are not going to be included in calculations.

While assuming full coverage of vegetated roofs would be an ideal scenario, it is not realistic anytime soon. Instead, different adoption rates calculated below help to understand

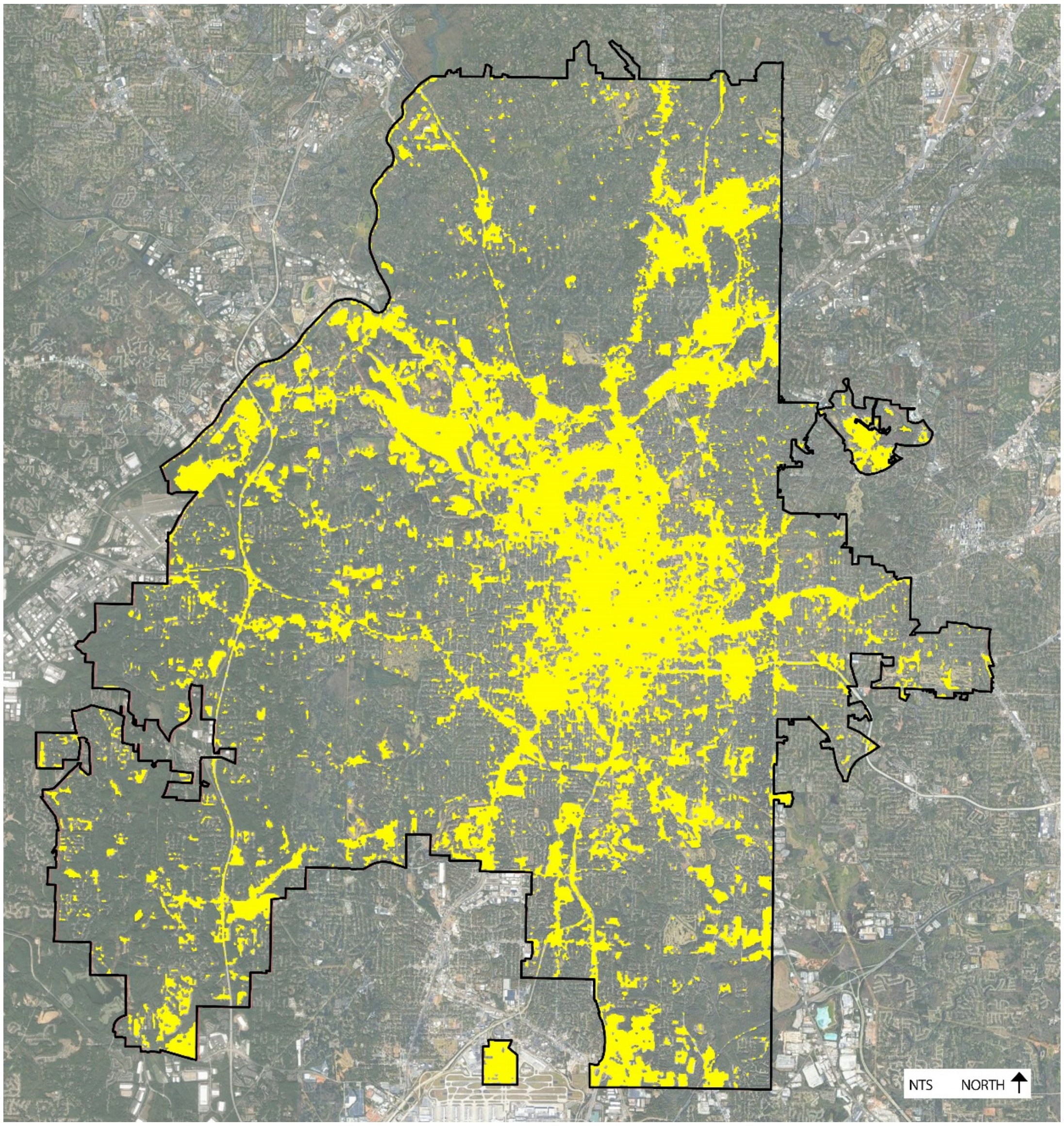

Figure 11: Areas of the city not covered in vegetation as of 2019.
Sources: (ESRI 2020); (Google 2020b).

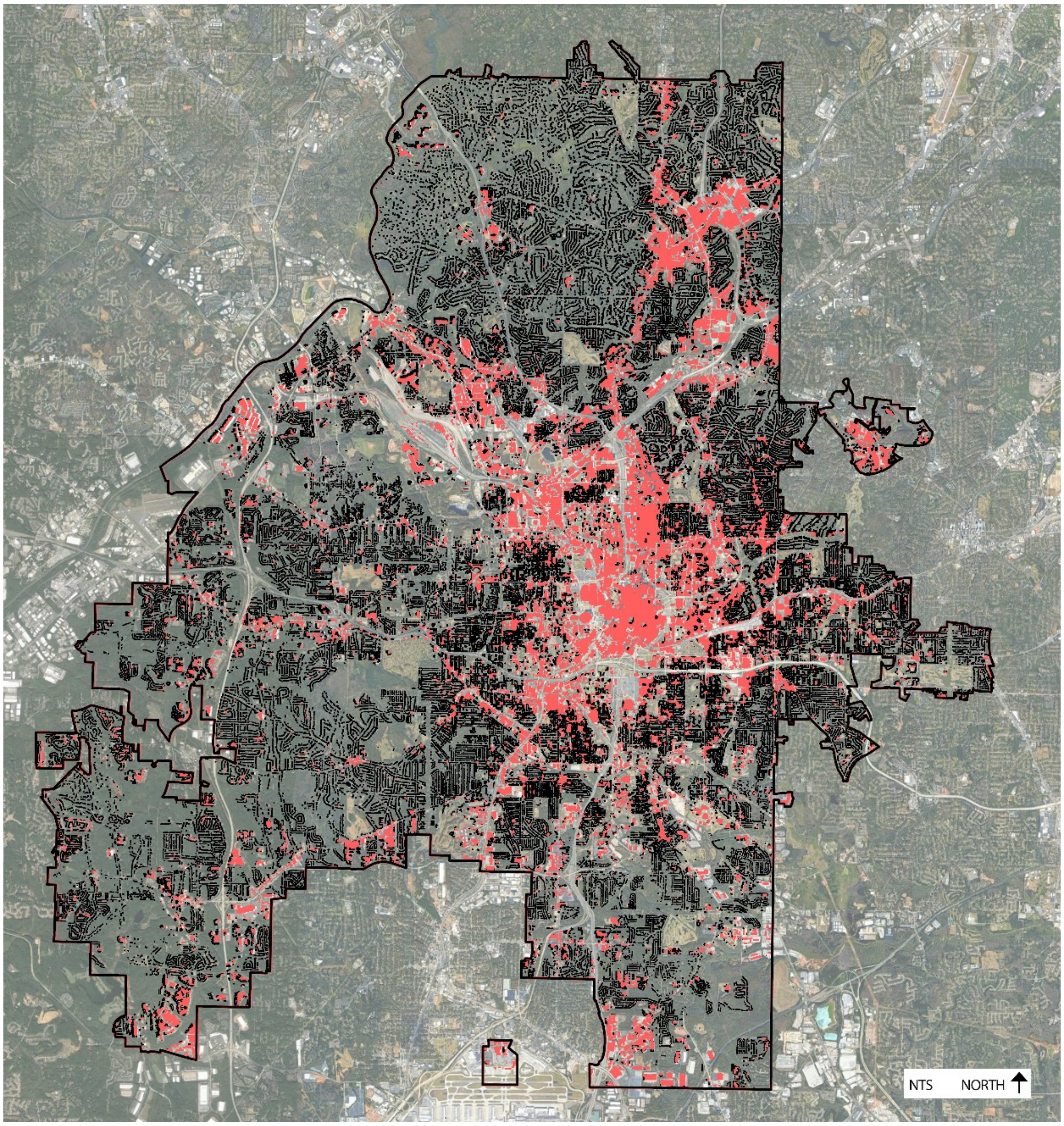

Figure 12: Rooftops not within areas of vegetation as of 2019.
Sources: (City of Atlanta 2018); (ESRI 2020); (Google 2020b).

Table 6: Area percentages and building coverages for different zoning types.
Sources: (City of Atlanta 2018); (Department of Planning and Community Development 2016).

Zoning Type	Percent Coverage of City Land by Type	Total Building Footprint Area	Zoning Type Building Coverage
		386,666,837	
Residential	7.11		27,492,012
Commercial	6.60		25,520,011
Office	3.70		14,306,673
Mixed-Use	6.70		25,906,678
Industrial	8.30		32,093,347
Community Facility	1.50		5,800,002
Business Park	0.0045		17,400
Total	**33.9145**		**131,136,123**

potential benefits for the future, as well as later on down the road if policy is adopted and vegetated roofs begin to be implemented on all projects.

Green Roofs for Healthy Cities conducts industry surveys most years in hopes to understand implemented square footage of vegetated roofs annually. From 2009-2018, an average of 5.27 million SF of vegetated roofs have been implemented annually across North America (“Green Roofs for Healthy Cities” n.d.). While this number is not 100% accurate for the total installation due to some members not taking part in the survey, it helps to better understand what reasonable installation rates could be for the city of Atlanta. If the city committed to installing just 1% of the 131 million SF available for implementation, Atlanta would account for almost 25% of the total annual implementation conducted through Green Roofs for Healthy Cities’ surveys. If that were to happen, the 20,000 SF vegetated roofs (n=65.568) could lead to the following annual benefits for the city:

n=65.568;

750,901.78 kg of CO_2 removed

1,265.00 – 2,081.98 kg of pollutants removed or avoided

25,951,683.30 gallons (79-acre-feet) of stormwater runoff reduced

$127,470.09 in annual electricity savings

$12,539.88 - $63,826.51 in savings due to CO_2 removal

$13,713.55 - $23,158.62 in savings due to air pollutant removal

$2,384.05 in avoided water treatment costs

In comparing these benefits with those of a red maple provided by the USDA Forest Service, it would take over 4,800 mature red maples to remove the same amount of CO_2, over 1,525 to equal the low end of air pollutants removed, and over 5,400 red maples to remove the same amount of stormwater runoff. While this may not seem like a lot of trees, especially when installation costs are considered, these replacement stats take into account the average benefits of a mature, 40-year old tree. Since younger trees contribute far less to ecosystem services than older trees, the above numbers would need to be tripled if planting 10-year old trees. In the case of stormwater reduction, over 32,000 10-year old trees would be needed. (McPherson et al. 2006)

If Atlanta were to adopt other rates of implementation, the results could be even higher (Table 7). In looking at adoption rates of 5%, 10%, 25%, 50%, and 100% coverage of available rooftops, the potential benefits to the city of Atlanta could be unlike anywhere seen in major cities around the world. A 10% coverage, or just over 13 million SF, could see the removal of over 7.5 million kg of CO_2, between 12,650-20,819 kg of air pollutants removed, almost 260 million gallons (798-acre-feet) of stormwater runoff reduced, and a total savings between $1.5-2.1 million USD annually. In the most ideal of all scenarios, with 100% adoption of extensive vegetated roofs, these results would multiply ten times, resulting in over 75 million kg of removed CO_2, 126,000-208,000 kg of removed air pollutants, almost 2.6 billion gallons (7,980-acre-feet) of reduced runoff, and $15-21 million USD saved annually through these ecosystem services. If the same stats from the USDA Forest Service were applied in comparing a 100% adoption rate to that of urban trees, over 486,000 mature red maples would be needed to provide the same CO_2 removal. At least 152,500 mature trees would be needed for the equivalent air pollutant removal and over 540,000 trees would need to be added to the city in order to see the same stormwater reductions. As before, these are mature tree calculations. If 10-year old trees were planted, over 3.2 million would need to be added to equal the runoff reductions of 100% vegetated roof coverage. (McPherson et al. 2006)

These calculations only look at a portion of the total savings and benefits. Not calculated, but which could be cause for further study, are the monetary benefits to human health, workplace benefits due to less missed days at work, added real-estate value, thermal comfort due to reductions in the UHI, and other social values brought about due to the addition of extra greenspace.

One of the greatest benefits of vegetated roof development, other than those listed above, is the fact that their development, and the ecosystem services they provide, requires no extra space within the city. Bare rooftops are in abundance throughout Atlanta, with more added every year in new construction. While the city does have open land at the ground-level for tree planting opportunities, finding the space to plant 3.2 million trees needed to equal the stormwater reduction capabilities of 100% vegetated roof coverage would be rather difficult. In remembering back, Trees Atlanta planted close to 88,000 trees between 1985-2013. They would need to plant more than 36 times that in order to get to 3.2 million.

Table 7: Vegetated roof adoption rates and benefits to the city of Atlanta

Available Rooftops in Atlanta = 131,136,123								
Adoption Rate	Equivalent SF of Rooftops	CO2 Removed (kg)	Air Pollutants Removed (kg)	Stormwater Runoff Reduced (Gallons)	Electricity Savings ($USD)	CO2 Savings ($USD)	Air Pollutant Savings ($USD)	Water Treatment Savings ($USD)
1%	1,311,361.23	750,901.784	1,265.00 - 2,081.98	25,951,683.30	127,470.09	12,539.88 - 63,826.51	13,713.55 - 23,158.62	2,384.05
5%	6,556,806.15	3,754,508.920	6,325.00 - 10,409.90	129,758,416.50	637,350.45	62,699.40 - 319,132.55	77,147.30 - 106,233.25	11,920.25
10%	13,113,612.30	7,509,017.840	12,650.00 - 20,819.80	259,516,833.00	1,274,700.90	125,398.80 - 638,265.10	154,294.60 - 212,466.50	23,840.50
25%	32,784,030.80	18,772,544.600	31,625.00 - 52,049.50	648,792,082.50	3,186,752.25	313,497.00 - 1,595,662.75	385,736.50 - 531,166.25	59,601.25
50%	65,568,061.50	37,545,089.200	63,250.00 - 104,099.00	1,297,584,165.00	6,373,504.50	626,994.00 - 3,191,325.50	771,473.00 - 1,062,332.50	119,202.50
100%	131,136,123	75,090,178.400	126,500.00 - 20,8198	2,595,168,330.00	12,747,009.00	1,253,988.00 - 6,382,651.00	1,542,946.00 - 2,124,665.00	238,405.00

While the argument for vegetated roof implementation and the benefits they can provide for the city is strong, the cost of implementation should not be overlooked. By using average installation costs provided by the U.S. General Services Administration, as well as by Yang, Yu, and Gong (2008), it can be assumed that an extensive vegetated roof could cost between $10.30-14.70 USD/SF, compared to a typical bare roof of around $7.00 USD/SF (U.S. General Services Administration 2011b) (Yang, Yu, and Gong 2008). At these costs, a 1% implementation strategy for vegetated roofs in Atlanta could cost between $13.5-19.3 million USD, whereas bare roof costs for the same SF could be just less than $10 million USD. At the other end of the adoption rate scenario, a 100% coverage plan could cost between $1.35-1.93 billion USD, where the same SF of bare roofs could be less than $1 billion USD. This just takes into account extensive vegetated roof costs. If the rooftops were semi-intensive or intensive, the costs could be even higher.

Modeled adoption rates have been added to the map of existing buildings (Figure 13) in order to better visualize the impact which each level of implantation could have on Atlanta. Without knowledge of each buildings zoning and use, it is not possible to distribute the graphics evenly among non-single-family residential buildings. Instead, an “epicenter” of development has been located in downtown, just southeast of Centennial Olympic Park. Each adoption rate percentage shows a different sized circle, representing the overall coverage of vegetated roofs for that individual rate. Coverage is shown on rooftops which occur in areas not covered in vegetation, as those could be the best candidates to first to receive vegetated roofs in the city. Further studies could map out more detailed zoning areas, square footages, and building structural capacities in order to more accurately show which rooftops would be able to support vegetated roof development throughout the city. One important thing to keep in mind is that while the adoption rates are 1%, 5%, 10%, 25%, 50%, and 100% coverage, these percentages are based off of available rooftops specified earlier. If figured into the percentage of total rooftops within the city, these rates range from .33-33.9% coverage for Atlanta.

Figure 13: Graphic representation of vegetated roof adoption rates in Atlanta.
Sources: (City of Atlanta 2018); (Google 2020b); (ImageJ n.d.)

CHAPTER 5

CONCLUSION

The origin of this thesis started many years ago by simply looking out the office window onto the unvegetated roofs of Atlanta and wondering what they would look like if covered with vegetated roofs. The overall research question grew to not only wondering about the ecosystem services of vegetated roofs on the city of Atlanta, but also questioning whether vegetated roofs had the ability to offset the loss of tree canopy due to development and urban growth. This thesis is structured in such a way as to research the history of urban development in order to gain an understanding of past, present, and future trends as they relate to density, growth, and effects of that growth. Following, the resulting change in climate is briefly touched upon, highlighting the negative impacts that un-checked development can have to urban areas in terms of air pollution, water runoff, and public health. The idea of green infrastructure to combat these changes has been around for a long time, but has mainly consisted of planting trees within urban areas. It was not until the mid-1900s that cities started looking up to the roofs and wondering what part they could play in climate mitigation.

While the use of vegetation on rooftops is not a new idea, their use for ecosystem services and to combat environmental hazards in urban areas is gaining traction. When first developed thousands of years ago, vegetated roofs were more for necessity in harsh climates or for personal satisfaction. When Germany started leading the charge in implementing vegetated roofs, a paradigm shift began and other cities soon followed. After noticing the results from Germany, cities such as Toronto, Chicago, and Portland all began research and have since adopted their own vegetated roof policies. Other cities such as Washington, D.C. and New York

City have also since begun implementing vegetated roofs and have joined Toronto, Chicago, and Portland as some of the most vegetated cities in North America.

Through policy research, findings show that many cities began implementing mandates around vegetated roof development. Some of these were based on individual environmental issues, such as stormwater runoff, an existing lack of greenspace, or increased UHI. Policies are generally based on pilot projects, incentives, or mandates and can be written to allow for added FAR on buildings which include vegetated roofs, or they allow credits on different fees such as stormwater. One of the biggest disadvantages of vegetated roofs is the initial cost of construction, which is why they are still rare on developments. Policies and incentives can help reduce the initial cost on the developer and can help promote their use in urban areas. While Atlanta has a stormwater ordinance which calls for the capture of the first one inch of rainfall on-site, the city does not have any policies or mandates surrounding vegetated roofs. In fact, many of Atlanta's sustainability documents do not mention plans for vegetated roof development. The 2010 Sustainability Plan for the city makes no mention of vegetated roofs. The 2016 Comprehensive Development Plan cites vegetated roofs as an alternative for lost forest land, however states no plan of action for their implementation. Lastly, the 2018 Green Infrastructure Strategic Action Plan does not mention any plan for vegetated roof development. The only mentions of vegetated roofs are through two existing images, a green infrastructure diagram, and sentence which mentions that vegetated roofs are a possibility for green infrastructure. If Atlanta wants to become a leader in sustainability, green infrastructure, and environmental health, the city needs to conduct more targeted research on the benefits of vegetated roofs and write a policy calling for their implementation. This could kickstart a green revolution in the city and help Atlanta to be an example for those to follow.

Through the initial literature review on the economic, environmental, and social benefits of trees and vegetated roofs, it is concluded that vegetated roofs are actually not able to offset the loss of the tree canopy due to urbanization. While vegetated roofs are able to provide greater building energy savings and stormwater retention than trees, trees are able to capture and store higher quantities of air pollutants and carbon. Another limiting factor for the development of vegetated roofs is their inability to equal urban trees in cost of implementation. While 19 m^2 (204 SF) of a vegetated roof is able to remove the same pollutants as a medium-sized tree, the vegetated roof costs almost eight times more than the tree. Even though vegetated roofs are not able to offset the loss of the urban tree canopy, they can supplement the urban tree canopy with added ecosystem services in the fight against climate change, air pollutants, and the overall health and welfare of urban areas.

The second part of the thesis looked into precedent studies in order to gain a better understanding of existing projects and their local benefits, as well as projective design on the quantifiable benefits which vegetated roofs could have to the city of Atlanta, Georgia. Through research, it is concluded that many of the examples found through the precedent studies could easily be adopted in Atlanta. For example, the city hall pilot projects which helped kickstart vegetated roof development in both Toronto and Chicago could have the same impact on Atlanta. Atlanta already has a small vegetated roof on a section of city hall; however, the proper care, maintenance, and research has not been kept in order to generate a trend of vegetated roof development. Two of the precedent studies are located on top of convention centers in Vancouver and New York City, which could be translated onto the roof of the GWCC at a much larger scale. At over 1 million SF in size, an extensive vegetated roof on the GWCC would make it one of the largest in the world and would almost cover 1% of available rooftops in Atlanta alone.

Lastly, although technically not within the city limits of Atlanta, Hartsfield-Jackson International Airport could serve as a shining example of vegetated roofs for the entire city. Similar to the Frankfurt International Airport, Hartsfield-Jackson has ample rooftop space for the implementation of vegetation. Since airports are largely impervious surfaces and void of any canopy cover, a vegetated roof could assist in environmental benefits, provide acoustic protection, and could serve to market the city's efforts in vegetated roof development, as Hartsfield-Jackson is the busiest airport in the world.

Following the precedent studies, projective design modeled and quantified benefits of an individual extensive vegetated roof in Atlanta. This method estimated that a typical 20,000 SF roof could remove over 11,000 kg of CO_2, 19.29-23.77 kg of air pollutants, reduce runoff by close to 400,000 gallons (1.22-acre-feet), and save between $2,800-$2,900 in total costs annually.

Total square footage of available rooftops for vegetated roof development in the city of Atlanta was found to be over 131 million SF. Different adoption rates of 1%, 5%, 10%, 25%, 50%, and 100% were projected out in order to gain an understanding of the overall impact that vegetated roofs could have on the city of Atlanta. Compared to the past ten years of average vegetated roof development in North America, if Atlanta implemented vegetated roofs on just 1% of available rooftops in the city, the city would account for close to 25% of the average annual implementation in North America.

While 100% coverage of vegetated roofs on available rooftops would be the most ideal scenario, implementation costs and feasibility likely mean that cannot happen anytime in the near future. If Atlanta were to take a serious look at vegetated roof development, there is no reason the city could not implement between 0.5-1% of available rooftops per year. If this were to happen, the city could see the implementation of between 655,680-1,311,361 SF of vegetated roofs per year. Assuming positive economic growth, the city could develop a quarter of available rooftops over the next 20-30 years. Depending on policy implementation, knowledge dissemination, and public opinion/support, this timeframe could be achieved even faster, making Atlanta a global leader in sustainability.

While this thesis looked into models and formulas in order to determine site specific benefits of vegetated roofs, future research can be conducted using dry deposition modeling with computer programs, or through construction of test plots within the city. These could help to gather more specific site benefits, such as the benefits possible to the UHI, as well as gather even more accurate pollution removal figures for different types of vegetated roofs and different plant material. Research could also gather more information about the existing buildings throughout Atlanta in order gain information about the slope, age, condition, construction accessibility, and structural capacity of their rooftops. Since the projective design focused on areas in Atlanta not zoned for single-family homes, this research could start with the buildings which fall into that area of research. This could help to forecast economics by understanding when existing roofs would be up for replacement. This could also assist in understanding what retrofit possibilities are in terms of which type of vegetated roof could be implemented based on structural capabilities.

Lastly, this thesis did not study the individual effects of different plant material in the Atlanta region. Further studies could examine different designs and plant material based on different types of vegetated roofs in order to produce a standard template of the most successful plant material for Atlanta's vegetated roofs.

The city of Atlanta is a wonderful place to live. Its diversity, moderate climate, and proximity to many different natural land features make it both a destination to those who do not live here and a proud home to those who do. The city is lucky to have such a lush forest at its doorstep and ample canopy coverage throughout its city limits. Being such a large city, Atlanta has ample amounts of bare rooftops waiting to be transformed with vegetation. The world is experiencing rapid urbanization and climate change. If Atlanta wants to assist in combating these issues, vegetated roofs be a major step to supplement the existing tree canopy in order to not only be known as the city in the forest, but also the city under the sedums.

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