QUANTIFYING ECOSYSTEM SERVICES OF GREEN INFRASTRUCTURE IN AUSTIN, TEXAS

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Executive Summary

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The City of Austin, Texas is evaluating a new landscape ordinance called Functional Green, which is intended to integrate nature into the city and meet the growth demands. With this ordinance, it is anticipated that 10,000 acres of the city’s highest developed land will be transformed with a minimum criterion of green infrastructure. In order to move forward with this ordinance, I teamed up with The Nature Conservancy and the City of Austin to work together on demonstrating the evidence that green infrastructure provides ecosystem service benefits to the city.

Green infrastructure is the network providing urban areas with the ingredients for solving urban and climatic challenges by building with nature. This includes landscape elements that give urban spaces a similar functionality to natural spaces.

Ecosystem services are an innovative concept designed to describe how natural resources and practices interact with and benefit human life. They are primarily the benefit that nature provides humans and are important drivers in how we prioritize conservation.

This project focused on eight landscape elements, including:

- Existing Trees
- New Trees
- Green Roofs
- Rain Gardens
- Vegetated Walls
- Plant Beds
- Porous Pavement
- Cisterns

We also analyzed eight ecosystem services, including:
There were three main objectives of this project:

1. Scoring Landscape Elements: creating a scorecard representing different landscape elements on their performance in providing ecosystem service benefit
2. Cost Benefit Models: analyzing existing buildings in Austin with different variations of green infrastructure and compare their costs of implementation with the ecosystem services that their landscape elements provide
3. Benefit Locations: identify areas of the city that are the most vulnerable and in the most need of the ecosystem services

Scoring the landscape elements involved an extensive literature review to summarize estimates of the supply, value of ecosystem services, and economic value provided by the landscape elements. Where there were gaps in the literature on the economic value we relied on interviews with City of Austin staff. Cost was also estimated by literature review and estimates from City of Austin’s experience in installation and maintenance of landscape elements.

In comparing the cost and benefits, a calculator was created in Microsoft Excel that allowed the values of the literature review to be multiplied by the square footage of green infrastructure for five existing buildings. Using this tool we were able to calculate and compare ecosystem services benefits, economic benefit and costs of implementation.

Finally in identifying the benefit locations of Austin multiple maps and tools were made to help the city understand where Functional Green will provide the most benefit. A map of tree planting prioritization was used as a proxy for identifying areas for green infrastructure prioritization. A GIS tool was created to allow planners to pick a zip code and see how much of the area is in the 10,000 highest developed acreage. It also anticipates the ecosystem services if that acreage had the same landscape elements as the different buildings from the cost benefit model. Lastly, survey data was used to locate locations in Austin where people are the most displeased with ecosystem services like stormwater.
The major results from the project include the discovery of how beneficial certain landscape elements are at providing a range of services, like existing trees and green roofs. It was also unveiled that buildings with higher diversity of expensive landscape elements are not necessarily more effective in providing benefit, unless they implement those elements that provide more ecosystem services. Lastly, there are multiple zip codes and census blocks along Interstate 35, within the Functional Green anticipated footprint, that can be identified as areas of the city that could benefit the most from these services.

Finally, we created a recommendation for the City of Austin in implementing Functional Green in the future. The city should provide some incentives for private land developers to construct the more beneficial landscape elements, rather than just the cheapest. There should also be a city-wide survey to gain information from the public’s perceptions of green infrastructure and possibly obtain more ecosystem services from equitable engagement in this process.

Approved

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25 April 2019
Date
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I. Introduction

Austin, Texas is quickly becoming one of the fastest growing cities in America. In order to regulate a rising population and diminish urban sprawl, cities around the world are innovating new, creative ways to make urban environments, healthier, safer, and more livable than ever before.

One of the ways many major cities are supporting urbanism is through the construction of green space throughout the grey space. Parks and urban forests have many proven benefits to the environment and to people but are typically very large projects that require a lot of space, consultation, and funding.

Green infrastructure is a simpler method to achieving similar benefits to green space but is integrated as a piece attached to the built environment. The landscape elements that make up green infrastructure, are anticipated to provide certain ecosystem services. For example, many green infrastructure elements provide air pollution removal, which offers people clean air to breathe. Another example is the aesthetic value that is beneficial for not only property value but also general happiness to the residents.

Although there is evidence that green infrastructure is beneficial, there is a gap in scientific literature on how cities make decisions based on the benefits. Austin is attempting to fill this gap by documenting the scientific evidence for ecosystem service benefits and how those benefits influence the proposed weighting of landscape elements. In Austin’s overall comprehensive plan, “Imagine Austin”, there is an environmental element which includes a planning tool called “Functional Green”. Functional Green aims to integrate green infrastructure and ecosystem services into the built environment. Eventually Austin will require the 10,000 acres of developed area to meet a ratio of green infrastructure. When the area starts construction, this will be a groundbreaking project that leads by example in creating a city green infrastructure plan supported by ecosystem service benefits.

This project is a collaborative effort between The City of Austin, The Nature Conservancy, and Duke Nicholas School of the Environment in providing the evidence necessary to carry out Functional Green. This report provides recommendations for the city and private land developers based on methods involving scoring landscape elements in regard to ecosystem service, a cost benefit analysis of current
Austin buildings compliant with green infrastructure ratio, and identified areas of the city that could use the most benefit.

II. Background

Ecosystem Services

Ecosystem services are an innovative concept designed to describe how natural resources and practices interact with and benefit human life. In 2005, the Millennium Ecosystem Assessment (MA), a pivotal work involving over 1,300 scientists, formalized a definition and classification of ecosystem services that is still widely recognized and used. The MA defined ecosystem services concisely as, “the benefits people obtain from ecosystems” (MA 2005, page v). Food, clean air and water, fiber for our clothes are all significant examples of services the environment provides humanity every day. However, there are many services the environment provides, that aren’t always very obvious. Benefits of clean air can be expanded even further to services like longer life expectancy, saving money on asthma medication, and even combating climate change in the long run. The services the environment provides, unfolds to much more service that effect social welfare and economic benefit.

Green Infrastructure

Green infrastructure is a term used for the landscape elements that provide urban areas with the functionality of natural areas. This can include anything between city parks and urban forests, to porous pavements and rain gardens. Green infrastructure planning has been proven successful in many European cities with provided benefits. Many cities have actually implemented programs that require urban development to incorporate landscape elements that enhance city ecological function.

Scope

Austin is the ever-growing urban capital of Texas, located at the intersection of a few major ecological regions, creating a highly variable climate. The Austin region gains hundreds of residents daily, largely due to the attractive culture of music, film, and art, but also the gaining number of major technology companies establishing major operations in the city. Texas as a whole is commonly identified as one of the least eco-friendly states in the country, but Austin has frequently ranked in the top 20 “greenest” cities (McCann 2018). Austin typically scores well in number of farmers markets per capita and air
quality despite the its transportation metrics compared to the other 100 most populated U.S cities (McCann 2018). Being the greenest city in Texas however, comes with the responsibility of leading by example on how to change the way cities are designed, in order to create a more eco-friendly community.

**Functional Green**

In 2012 the Austin City Council unanimously adopted “Imagine Austin”, the city’s comprehensive plan through 2040. The plan was created with thousands of Austinites input to establish a community where all citizens have access to the amenities, transportation, services, and opportunities that fill their need. These communities will provide a livable, safe, affordable, and accessible city that promotes healthy lifestyles, community engagement, and inclusion.

As part of the plan’s “environment” priority to manage Austin’s urban and natural ecosystems in a coordinated and sustainable manner, “Functional Green” was created. Functional Green is an environmental planning tool that aims to integrate nature and ecosystem services into new built environments. The tool will eventually be used to require urban developments in the highest developed 10,000 acres of the city, to incorporate landscape elements that enhance ecological function.

In a report conducted by The Nature Conservancy, the Regenerative Environmental Design Group and the ECONorthwest Planning Group, many cities around the world are implementing similar tools, using a Biotope Area Factor (BAF). Also known as a Green Space Factor or a Green Area Ratio, Biotope Area Factor is an environmental metric and planning tool for increasing the ecological performance and vegetated area of the urban environment. Biotope Area Factor represents the ratio between ecologically effective surface area and the total project area. To calculate the performance rating, the total area of each landscape element is determined, then multiplied by an established factor. The values of all landscape elements are summed and then divided by the total area of the site.

\[
BAF = \frac{(area\ A \times factor\ A) + (area\ B \times factor\ B) + (area\ C \times factor\ C) + \ldots}{total\ site\ area}
\]
For each element (A, B, C, and so on) the factors assigned to the different landscape elements vary based on their relative environmental performance and aesthetic values. Elements with priority ecosystem services are typically given higher factors.

Minimum BAF target scores vary depending on the building types and location. Target scores represent the minimum percentage of the site that provides ecosystem services. The goal of BAF is to set realistic minimum levels that are achievable while also beneficial in ecosystem service value. Generally, a BAF plan review will determine the target project scores through comparison studies of existing landscape code and BAF requirements, experimental design case studies that explore the green potential of sites, and the goal of city planners.

In The Nature Conservancy’s review of BAF reports and documents, there was consistent noting of environmental benefits of landscape elements, but none of the programs provided literature reviews of the science that informed decision making or discussed the processes used to determine the landscape element value. There was also a lack of literature providing details on the estimated performance and post-occupancy monitoring of the BAF projects.

In terms of the City of Austin, Functional Green is anticipated to use a Biotope Area Factor tool to support the city in developing a reasonable level of beneficial green infrastructure. The City of Austin is taking a leadership role by documenting the scientific evidence for ecosystem service benefits that influence the proposed weights of the landscape elements in Functional Green.

III. Objectives

This project consisted of three objectives to aid the City of Austin. Ideally the accumulation of these objectives will allow the city to create standards for the Biotope Area Factor, consider if the Functional Green footprint is the most appropriate area in need of the ecosystem services, and make decisions on how this project is feasible for private land developers.

A. Scoring Landscape Elements

Because the city was interested in particular landscape elements and ecosystem services, The Nature Conservancy decided the most efficient way to interpret the performance of green infrastructure at providing benefit is through a scorecard. Scorecards have been successful in providing meaningful information describing how well elements act in particular categories.
The purpose of providing the scorecard is to illustrate what landscape elements are more effective at providing benefit and by how much. This is information that the city, as well as private building developers can use to identify what landscape elements can and should be added to their development in order to maximize the ecosystem services for their Biotope Area Factor.

B. Cost-Benefit Models

The city was also interested in how green infrastructure is effective at an economic standpoint.

The results of identifying the costs of constructing the landscape elements and the benefits from the ecosystem services is important for the city to understand what they should expect from the implementation of Functional Green. The cost-benefit calculator will allow the city to simply understand the costs and the benefits associated with the square footage of green infrastructure elements as shown by the literature. By already quantifying the costs and benefits of already existing buildings in Austin that have varying levels of green infrastructure before the pressures of Functional Green, the city can understand the feasibility and variations on what is most beneficial.

C. Benefit Locations

Identifying the locations of the city that are going to benefit the most from the benefits of Functional Green is another important objective that the city could learn a lot from. Functional Green already has a determined footprint representing properties in the city's urban core that that would be allowed over 80% impervious cover based on the land development code update in the works during 2017, and areas outside the urban core that are properties that are already over 80% impervious cover. Proximity to this footprint is surely to benefit more, the closer one is. It is also important to notice if the Functional Green footprint should be extended if it is not providing services to the most vulnerable communities of the city.

IV. Methods

A. Scoring Landscape Elements

The City of Austin was most interested in evaluating particular landscape elements based on their reputations of ecosystem benefit and economic values. These elements include: planting street trees; installing green roofs; planting rain gardens and other bioretention structures; installing green façades
on buildings; substituting porous pavement for asphalt or cement roadways; and collecting rainwater via cisterns or similar catchment systems. All of these landscape elements, also known as “low impact development” and “green infrastructure”, are of interest to The City of Austin based on the following landscape roles:

- Reducing stormwater volumes by infiltrating it into the ground or releasing it over time into a city’s stormwater pipes and other “grey” stormwater infrastructure.
- Filtering stormwater onsite and improving downstream water quality.
- Reducing downstream flooding.
- Improving air quality with vegetation that sequesters carbon, removes particulate matter, and captures other air-borne contaminants.
- Moderating air temperatures and mitigating urban heat island effects.
- Providing habitat value and resources for biodiversity.
- Providing visual amenities.

Economists also value the benefits these elements provide. There is the avoided-cost method, which estimates benefit values based on the amount and cost of municipal services avoided because of the landscape elements in place. An example is the volume of stormwater kept out of a jurisdiction’s system of stormwater pipes and treatment facilities, and the associated cost savings of not having to process this volume of stormwater. Hedonic analyses estimate the impacts of landscape components on nearby property values. These analyses control for property-specific attributes, e.g., number of bedrooms, size of lot, school district, etc. and estimate the resulting impact on property values from landscape components, e.g., street trees. Contingent valuation studies estimate people’s willingness to pay to protect landscape attributes. For example, this type of study might estimate the value that residents place on the habitat benefits provided by a city’s green roofs.

The state of the science of ecosystem services is such that the available data are typically insufficient to allow quantifying and valuing all ecosystem services from all green infrastructure applications. While the body of relevant literature and data continues to grow, much work remains to fill gaps in quantification and valuation. One should also consider that the supply of ecosystem services and their
associated economic benefits can be very site specific. Natural elements like local soils, landscape and climate conditions can influence the benefit and supply of ecosystem services. These conditions, plus local cost of services, property values, etc., can influence the ecosystem service values. For this reason, care must be taken when considering using supply and value estimates from past studies conducted elsewhere.

The purpose of this literature review is to summarize estimates of the supply and value of ecosystem services provided by six key landscape elements expected to be included in the City of Austin’s Functional Green program. This review focuses on the relationship between the landscape elements and the magnitude and quality of ecosystem goods and services that flow from the landscape. Using Google Scholar, for each of the landscape elements, we review relevant ecosystem services literature from four perspectives: (1) biophysical benefits, (2) economic values, (3) beneficiaries, and (4) costs of implementation. Whenever possible, we refer to studies conducted in the Austin area or in locations with similar climate conditions (humid subtropical climate zones as classified by Koppen Climate Classification System). In cases where Austin-specific data are not available, we report results from studies conducted elsewhere. In some cases, the available data do not allow quantification or valuation of an ecosystem service, so we describe supply and value qualitatively. Over 150 published, peer reviewed articles were evaluated.

For the technical review of biophysical benefits, we relied on the results of the literature review and additional studies on each landscape element. Technical performance was categorized into several key ecosystem service types prioritized by the City of Austin: (1) microclimate regulation and mitigation of urban heat island effects, (2) carbon storage and sequestration, (3) air pollutant removal, (4) stormwater retention and runoff reduction, (5) water filtration, and (6) biodiversity benefits. In addition, benefits to human well-being are summarized where data are available. Under each of these ecosystem service types, the relevant literature was summarized to provide an estimate of the range of likely benefits. We reviewed studies of performance for individual landscape elements in the field and lab as well as modeling studies that evaluated potential performance if landscape elements were broadly applied across an urban landscape.

Results for biophysical performance are summarized on a per-unit or per-area basis, and, where modeling studies are available, results are reported for implementation at broader spatial scales.
Although different studies often report different metrics for performance, we attempted to identify and report common metrics whenever possible to allow for comparison between different landscape elements.

The economic analysis of the costs and benefits of landscape elements also relied on the results of the literature review and interviews with City of Austin staff. Our analysis also identified the factors that influence the magnitude of economic benefits. The degree to which we were able to quantify economic benefits varied by landscape element. For some landscape elements and some benefits, data were available to identify per-unit values specific to the City of Austin. In some cases, per-unit values were not available for the City of Austin, but were available for other, similar geographies or as a national average. In cases where data on per-unit economic values were not available, we described the value qualitatively, focusing on the mechanism of economic effect, direction and magnitude of change, and other factors that may influence the value. We estimated costs similarly, relying on primary estimates from the City of Austin’s experience installing and maintaining the landscape elements where possible. If data were not available from the City of Austin, we relied on cost estimates from the literature. All dollar values are reported in 2015 equivalent dollars.

**B. Cost Benefit Calculator**

This information from the literature review and the scorecard was strategically calculated in Microsoft Excel to identify the ecosystem services provided per square foot of each landscape element.

**b.i Landscape Element Tab**

In the first tab of the calculator is the Landscape Element Tab. This tab includes multiplying the square feet of each landscape element (or gallons for cisterns) and multiplying that square footage by the low and high measurable ecosystem values from the literature review. Those measurable ecosystem service values are separated into low and high overall contributions to kilograms of carbon storage, kilograms of carbon sequestered per year, grams of air pollution removed per year, and gallons of stormwater retained per year. This provides the information of what the benefits are from for the ecosystem services depending on the square footage and gallons of green infrastructure.
b.ii Cost Tab

To consider cost of implementing the landscape elements, a Cost Tab was created. This tab considers the square feet of the landscape elements divided by the square feet per item (Important for shrubs. Cost is typically for 38 shrubs per square foot). This number is multiplied by a low and high anticipated cost per unit installed. The low cost is from the literature review of cost of installation and the high cost is suggested from City of Austin interviews. This calculation results in the low and high cost of implementation for each of the landscape elements.

b.iii Economic Benefit Tab

For calculating the economic benefit from the installed landscape elements, the low and high ecosystem services from the Landscape Element Tab were multiplied by the economic benefit per unit of element. This economic benefit is also measured in low and high and comes from the lowest and highest benefit identified in the literature review. This results in the low and high quantifiable economic benefit per landscape element for a building.

Lastly, to create applicability for the calculator, five already-existing buildings in Austin, with varying square feet and diversity of green infrastructure, were used to compare the ecosystem services, economic benefit and cost. The five buildings are a few of Austin’s apartments/condominiums and a hotel for comparison reasons. Below are the buildings and their overall square footage:

- The Arnold: 189,869 sq ft
- South Congress Hotel: 41,382 sq ft
- The Austonian: 28,850 sq ft
- 7th and Rio Grande: 25,376 sq ft
- The Galileo: 14,375 sq ft

For each of the buildings, the low and high ecosystem service benefits were calculated from the square feet of landscape elements in the Landscape Elements Tab, the low and high estimated costs were calculated in the Cost Tab, and the quantifiable economic value of the green infrastructure element was calculated in the Economic Benefit Tab.

Table 1: Landscape Elements for 5 Austin Model Buildings
C. Benefit Locations

To identify the places in Austin that would benefit the most from the ecosystem services, three ArcGIS evaluations were considered.

**c.i Austin Urban Street Tree Planting**

The City of Austin’s Tree Planting Prioritization is a decision supportive tool in GIS that locates tree planting areas throughout the city. The prioritization is based on eight broad categories: public health & safety, air quality, environmental justice, water quality, critical places, forest replenishment, forest preservation & development impacts, and urban heat island (Appendix 1). In all, a total of 31 planting factors were considered to derive priority tree planting areas. Each factor was quantified, standardized, and totaled creating a planting priority score for each Census tract. Priority scores can range from 0 to 8 with higher scores representing a higher need for tree planting. This tree prioritization was used as a proxy for Austin’s green infrastructure. Trees are included in the green infrastructure evaluation and this tool considers many categories similar to the ecosystem services benefits needed.

**c.ii Functional Green Zip Code GIS Tool**

Using GIS a model was created for a user to play with city planning and decide which Austin zip codes are going to benefit the most from Functional Green. Using the 5 buildings from the Functional Green Calculator, the buildings were reinterpreted as plans. The plans were based on their landscape...
elements and ecosystem services benefits. Using this tool, a user can select a zip code and see how the proposed plans benefit the city.

Because Functional Green is focused on the highest developed areas, we first created a shapefile of the highest developed zones in Austin using GIS. Using zoning data from The City of Austin we selected all attributes of zoning including Central Business District, Downtown Mixed Use, General Commercial Services, Multi-Family Residence between moderate and highest density, and all districts including Mixed Use Combining and Vertical Mixed Use Combining. We then summed up the total square feet of developed area within each Austin zip code. We then calculated a field to add up all of the high developed area per zip code.

With this new high development per zip code data, all of the zip codes that don’t have development high enough to meet the attributes were deleted. This included zip codes with values of 0 square feet of high development. Then the ecosystem services fields were added to the file.

We made 5 copies of the zip code file, one for each building plan. Each ecosystem service within that plan was then calculated with the calculations of benefit per square foot. We also added a field to the table to identify the name of the plan.

Finally, using the select tool we granted access to allow a user to choose a zip code between 78613 and 78759 as a parameter. From there, the tool selects that zip code from each plan and copies it into its own feature. At the end the tool creates a combined table of all of the expected ecosystem services for that zip code, according to each plan.

**c.iii Survey Data GIS Maps**

Lastly, when evaluating ecosystem services, it’s critical to recognize the public’s perception. In this case, the public’s opinion on green infrastructure elements and the ecosystem services they need.

Every year the City of Austin administers a community survey to assess satisfaction with the delivery of the major city services and help determine priorities for the community as part of the City’s ongoing planning process (“Community Survey 2015, 2016, & 2017”). Using this survey data, we were able to reference where people with the strongest feelings about city services lived and identify these areas as places with the highest need. From this survey data, the question that most related to our ecosystem
services was, “How satisfied are you with the overall management of stormwater runoff?”. In order to geospatially recognize this we tried to identify where the people that answered this question lived, and how satisfied they were.

The data retrieved by the city’s GIS portal was offered in an Excel sheet with over 30 questions and 6,375 responses that were later added to a GIS geodatabase. Using the XY data to points tool we were able to project the XY Block level data geographically.

Finally, adding the geospatial footprint of Functional Green, all of the survey respondents that were within 2 miles of Functional Green were selected and created into a new layer. 2 miles was used as a medium because it accounted those people that are going to be most affected by Functional Green on a daily basis and not people that live too far from high development.

V. Results

A.1 Scoring Landscape Elements

The results from the literature review and technical review are summarized below. We found that some landscape elements have a sizeable amount of literature defending their ecosystem service while others do not. With every landscape element below we provide an evidence grading table defending the biophysical and economic benefits that each landscape element provides in terms of ecosystem service.

1. Trees

   a. Biophysical Benefits

   Extensive research has been conducted on the environmental and social benefits of trees in urban landscapes. In Austin, Texas, a comprehensive study of over 200 field plots provided input data for the U.S. Forest Service’s iTree Eco modeling software in 2014 (Nowak et al. 2016). The field data collection and modeling effort allowed for a range of ecosystem services to be quantified in biophysical and economic terms for Austin’s trees. Trees within developed land uses account for approximately 40 percent of Austin’s urban forest, suggesting that the benefits of trees can be integrated throughout the urban mosaic and provide extensive benefits to citizens across the city.

   More broadly, previous research in urban landscapes indicates that urban trees are the most powerful generators of ecosystem services within highly developed environments as key providers of regulating,
supporting, provisioning, and cultural services (Nowak and Dywer 2007, Mullaney et al. 2015). Urban trees provide a broad range of biophysical benefits, including regulating microclimate, capturing air pollutants, sequestering and storing carbon, reducing stormwater runoff, and providing resources for biodiversity. Most of these benefits are correlated with the leaf area of the trees; larger trees and those with greater leaf area provide greater benefits than smaller trees or trees with less leaf area (Nowak et al. 2016). In Austin, trees with particularly high leaf area that may be included in streetscapes include live oaks and cedar elms.

a.i Microclimate Regulation

As microclimate regulators, trees provide shade by acting as structural shields from solar radiation (blocking 70 to 90 percent of incoming solar radiation on sunny days, Heisler 1986); they also provide cooling benefits on sunny days through evapotranspiration, which can disperse to provide an overall cooling effect at a broader spatial scale. Research in a humid subtropical climate (Maryland, USA) examined the collective effects of street trees on urban heat island effects and found that tree cover adjacent to urban roads can decrease surface air temperatures by 7° F (4.1K), road-surface temperatures by 27° F, and building wall temperatures by 16° F (Loughner et al. 2012). In Austin, the cooling benefits of trees have been quantified in terms of the projected energy savings that buildings could save on air conditioning costs due to tree location, size, and proximity to building walls and roofs, with a net savings of $18.9 million annually for residential buildings (Nowak et al. 2016). These energy savings also result in substantial avoided greenhouse gas emissions from power plants. The cooling effects of urban trees can also lead to reduced formation of ground-level ozone, an air pollutant linked with serious respiratory health effects (Nowak and Dywer 2007).

a.ii Air Quality, Carbon Storage and Sequestration

Trees also play a direct role in urban air quality, by storing and sequestering carbon, capturing gaseous air pollutants through leaf stomata, and intercepting particles on plant surfaces (Nowak and Dywer 2007). Collectively, Austin’s existing tree canopy contributes to the annual removal of 1,120 tons of O_{3}, 86 tons of NO_{2}, 24 tons of PM_{2.5}, and 23 tons of SO_{2} (Nowak et al. 2016). Some trees can emit volatile organic compounds (VOCs), which are precursors to O_{3} and CO formation; however, this process is temperature dependent, and the cooling effects of trees are expected to outweigh the effects of VOC emission (Nowak and Dywer 2007). Furthermore, trees take in carbon from the atmosphere as they
grow. One large healthy tree sequesters about 93 kg C per year (Nowak and Dywer 2007). Austin’s trees collectively store about 1.9 million tons of carbon in their biomass, with an annual net sequestration rate of 67,000 tons of C per year (Nowak et al. 2016). In urban areas, the vast majority of the carbon pool is stored in trees rather than herbaceous plants or smaller woody vegetation (Davies et al. 2011).

a.iii Stormwater Management

Trees also contribute to stormwater management goals in urban areas by intercepting rainwater and promoting infiltration and water storage in soil. This in turn leads to reduced peak flow and runoff volumes. An individual tree is estimated to reduce stormwater runoff volume by 113-400 cubic feet each year (Mullaney et al. 2015). Calculations performed by City of Austin staff suggest that the stormwater management benefits of trees (specifically interception of rainwater) are relatively low compared to the retention benefits of other green infrastructure such as rain gardens. The collective stormwater benefits of trees in Austin was estimated at 65 million cubic feet of “avoided runoff” each year (Nowak et al. 2016).

a.iv Biodiversity Benefit and Human Wellbeing

Trees benefit biodiversity by providing habitat resources and enhancing habitat connectivity across urban landscapes (Strohbach et al. 2013, Ikin et al. 2013, Belaire et al. 2014). Research also demonstrates that trees can contribute to noise reduction in urban areas (reviewed in Gomez-Baggethun and Barton 2013) and a variety of social benefits, including reduced crime (Kuo and Sullivan 2001) and improved road safety for drivers and pedestrians (reviewed in Tarran 2009).

Table 2. Range of Estimated Biophysical Benefits for Trees in Austin, Texas
### Ecosystem Service Type

<table>
<thead>
<tr>
<th>Ecosystem Service Type</th>
<th>Range of Estimated Biophysical Benefits in Austin, Texas</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Microclimate regulation and mitigation of urban heat island effects</strong></td>
<td>2.2-7.0°F reduction in surface air temperatures (for areas underneath and adjacent to street tree canopy)</td>
<td>Loughner et al. 2012, Shashua-Bar et al. 2009, Davis et al. 2016, and Wang &amp; Akbari 2016</td>
</tr>
<tr>
<td><strong>Carbon storage and sequestration</strong></td>
<td><strong>Storage:</strong> 7.7-28.9 kg C/m² <strong>Sequestration</strong> (on a per-tree basis): 11-64 kg C/year for small trees; 93-305 kg C/year for larger trees; average 0.28 kg C/m² tree cover per year</td>
<td>Nowak et al. 2013, Nowak &amp; Dywer 2007, Davies et al. 2011, Nowak et al. 2016, iTree Design v 6.0</td>
</tr>
<tr>
<td><strong>Air pollutant removal</strong></td>
<td>6.6–12.0 g of air pollutants removed per m² of tree canopy, depending on location, size and type of tree <strong>On a per-tree basis:</strong> 2.0-13.9 g CO per tree, 12.2-63.4 g NO₂ per tree, 56.0-93.3 g O₃ per tree, 23.4-83.3 g PM₁₀ per tree, and 7.1-34.6 g SO₂ per tree</td>
<td>Nowak &amp; Dywer 2007 (including per-tree calculations derived from Tables 1 and 2)</td>
</tr>
<tr>
<td><strong>Stormwater retention and runoff reduction</strong></td>
<td><strong>On a per-tree basis:</strong> 11-44 ft³/year for small trees; 113-400 ft³/year for large trees <strong>At broader scales:</strong> canopy coverage of 30% could reduce existing runoff volume by 12–13%</td>
<td>iTree Design v 6.0, Mullaney et al. 2015, Livesley et al. 2014, Sanders 1986</td>
</tr>
<tr>
<td><strong>Water filtration</strong></td>
<td>Can lead to reduced total pollutant loads due to some reduction of runoff volume.</td>
<td></td>
</tr>
<tr>
<td><strong>Biodiversity</strong></td>
<td>Increased biodiversity observed in areas of greater tree coverage</td>
<td>Ikin et al. 2012, Strohbach et al. 2013, Belaire et al. 2014</td>
</tr>
<tr>
<td><strong>Human well-being</strong></td>
<td>Potential contribution to noise reduction, reduced crime, improved road safety, and other social benefits</td>
<td>Gomez-Baggethun et al. 2013, Kuo &amp; Sullivan 2001, Tarran 2009</td>
</tr>
</tbody>
</table>

### b. Economic Benefits

The economic benefits of trees derive from their biophysical effects. For several of these effects, there is a strong body of literature assigning a dollar value to trees, including benefits arising from trees’ positive impact on air quality, local climate regulation, carbon uptake, and property values.

#### b.i Value of Air Pollutant Removal and Emissions Avoidance

Trees reduce air pollution by taking up and filtering pollutants already in the air, and by regulating local climate conditions, which can reduce energy use and associated air pollution. Economists measure the value of air quality improvements in several ways. The iTree Eco Modeling Software described above, and used in the Nowak et al. (2016) study of the value of trees in Austin, uses an approach that quantifies the avoided costs associated with pollutants’ effects on human health: as pollutant concentrations decrease, the costs associated with pollution-induced health conditions, such as premature death, respiratory conditions, and absenteeism due to illness also decrease. The iTree model integrates data from U.S. EPA’s BenMAP tool, which estimates the health impacts and economic value of changes in air quality. This modeling process accounts for local population density and age
characteristics where air quality benefits occur, because the value of diminished air pollution is greater where there are more people to benefit. Also, benefits are greater among older and younger populations, which are typically more vulnerable to air pollution. Table 2 shows the values from iTREE for rural and urban areas in Austin, showing the differences in value based on the population differences in different parts of the city.

Table 3. Value of Air Pollutant Removal (Dollars per Pound in 2015 Dollars)

<table>
<thead>
<tr>
<th></th>
<th>Values for the City of Austin (Nowak et al. 2016)</th>
<th>Values for a Rural Site in Austin</th>
<th>Values for an Urban Site in Austin¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen Dioxide (NO₂)</td>
<td>$0.14</td>
<td>$0.06</td>
<td>$0.15</td>
</tr>
<tr>
<td>Sulfur Dioxide (SO₂)</td>
<td>$0.04</td>
<td>$0.02</td>
<td>$0.04</td>
</tr>
<tr>
<td>Small Particulate Matter</td>
<td>$22.68</td>
<td>$12.00</td>
<td>$29.72</td>
</tr>
</tbody>
</table>

Sources: iTREE

Notes: ¹ This site is typical of the downtown area where Austin’s Functional Green program is focused.

b.ii Value of Carbon Emissions Avoidance and Carbon Sequestration

Trees provide benefits for global climate regulation by sequestering carbon and by regulating local climate conditions, which can reduce energy consumption by reducing building heating and cooling demand. The amount of carbon sequestration varies by species and age of the tree. The amount of carbon emissions avoided by reducing energy demand depends on local climate conditions and on the placement of trees relative to buildings.

Trees in Austin store (taking into account decomposition) approximately 67,000 tons of carbon each year, valued at about $8.5 million per year (Nowak et al. 2016, calculated based on reported information for value of gross carbon sequestered each year). Trees also offset energy demand which reduces carbon emissions from fossil-fuel-based power sources, valued at almost $5 million (Nowak et al. 2016). This equates to about $35 per ton of CO₂ offset or sequestered, which is based on the U.S. Council on Environmental Quality and the EPA’s recommendations for valuing the social cost of carbon. The EPA’s guidance on valuing carbon sequestration and avoided carbon dioxide emissions recommends using a value between approximately $12 and $65 per metric ton of CO₂ for emissions avoided or carbon dioxide equivalent sequestered in 2015 (Interagency Working Group 2016; dollars converted to 2015 based on the CPI; range depends on the discount rate used to adjust future
damages). This value accounts for the social cost of carbon emitted today, accounting for costs of effects associated with that unit of carbon that accrue over time. The value of a metric ton of carbon dioxide equivalent sequestered (or carbon dioxide emissions avoided) in the future (by 2050) increases to between $30 and $110, to account for the cumulative and increasing damages attributable to climate change (Interagency Working Group 2016; dollars converted to 2015 based on the CPI).

b.iii Energy Costs

Homes and other buildings with appropriately located trees may cost less to heat and cool. The amount of avoided energy costs depends on the location of the trees relative to the structure, the local climate, and the efficiency of the building itself. Multi-story and multi-family residential buildings experience fewer benefits than single-family residential buildings, because they are less influenced by shade effects of trees and more by climate conditions (McPherson and Simpson 2003). Even in areas dominated by multi-story buildings, a high density of urban trees helps reduce energy demand by reducing the urban heat-island effect, lowering ambient air temperature. Nowak et al. (2016) suggests that interactions between trees and buildings reduces the City of Austin’s residents’ energy costs by almost $19 million each year. This also reflects the offsetting effect that trees may increase heating demands during the winter, because they (especially evergreen species) provide shade when sun exposure would otherwise offset heating expenses. This offsetting effect is smaller for multi-story buildings, because they are less influenced by the shading effects (McPherson and Simpson 2003).

b.iv Property Values

Trees offer many amenities that contribute to property values. A review of studies comparing areas with street trees to areas without across the country found that street trees can add between 2 and 10 percent (potentially up to 15 percent for mature trees in high-income neighborhoods) to property values (Wolf 2007). A mature tree canopy throughout a neighborhood can add between 6 and 9 percent to the homes in the neighborhood. There has been comparatively little research on the influence of trees on the value of multi-family and rental dwellings, but limited research has found that in Portland, Oregon, street trees increase rents (Donovan and Butry 2011). Trees enhance the value of commercial property, by increasing the street appeal to potential consumers and potentially increasing sales, and by increasing rental rates and reducing turnover for commercial offices (Laverne and Winson-Geidman 2003; Wolf 2007). A study of property values in Austin found, using two different methods, that street
trees contribute between 13 and 19 percent of the value of residential property (Martin, Maggio, and Appel 1989).

**b.v Stormwater Runoff Costs**

Trees capture and absorb stormwater, which has the potential to generate several economic benefits. These include lower risk of flooding and associated damage, reduced storm/sewer overflow events and potentially improved water quality, and reduced capacity of stormwater management infrastructure in areas with trees, especially combined with bioretention. These benefits all have the potential to yield avoided costs and economic benefits for property owners and the city's taxpayers. Nowak et al. (2016) calculates that Austin's trees capture 65 million cubic feet of stormwater runoff each year. Putting a dollar value on that reduced runoff city-wide is challenging, but examples from elsewhere suggest trees can provide very large benefits. In Washington, D.C., the existing 46 percent tree canopy reduces the need for stormwater retention structures by 949 million cubic feet, saving the District $4.7 billion every 20 years (American Forests 2002). Using a national average of $2 per cubic foot of storage, Austin's trees would provide approximately $130 million in stormwater retention benefits every 20 years (American Forests 2002).

**b.vi Health and Biodiversity Benefit**

In addition to these benefits, the literature describes qualitatively additional economic values associated with trees, including health benefits, and benefits associated with increased biodiversity. A recent article attempted to value urban green spaces at the national level, evaluating studies associated with six social and health conditions that show improvement and reduced treatment costs when correlated with access to green spaces: newborn health, ADHD, school performance, crime, Alzheimer's disease, and cardiovascular health. The potential cost savings associated with improvements in these conditions ranges from $2.7 to $6.7 billion per year (Wolf 2015). Some of these benefits are likely at least partially captured by the valuation methods used for the benefits described before (e.g., property values and avoided costs of air pollution), but the quantified benefits almost certainly underestimate the total economic value generated by trees.

Table 4. Range of Estimated Values of Economic Benefits of Street Trees in Austin, Texas
<table>
<thead>
<tr>
<th>Economic Benefit</th>
<th>Range of Values of Economic Benefits for Austin, Texas</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Costs</td>
<td>Site-specific, depending on location of trees relative to building, baseline energy demand, and energy costs.</td>
<td></td>
</tr>
<tr>
<td>Carbon Sequestration</td>
<td>$44-$239 per metric ton of Carbon</td>
<td>Interagency Working Group 2016</td>
</tr>
<tr>
<td>Nitrogen Dioxide Removal</td>
<td>$0.13-$0.33 per kg</td>
<td>Nowak et al. 2016</td>
</tr>
<tr>
<td>Sulfur Dioxide Removal</td>
<td>$0.04-$0.09 per kg</td>
<td>Nowak et al. 2016</td>
</tr>
<tr>
<td>Avoided Stormwater Runoff Costs to City of Austin</td>
<td>$2 per cubic foot of stormwater diverted from system</td>
<td>American Forests 2002</td>
</tr>
<tr>
<td>Avoided Costs of Ecological and Species Habitat Management</td>
<td>Unquantifiable, but likely positive. Higher value for positive effects on habitat for sensitive species</td>
<td></td>
</tr>
<tr>
<td>Avoided Health Care Costs, Improved Human Well-being</td>
<td>Unquantifiable, but positive relationships have been measured at a national scale, attributing benefits of access to green space to reduced healthcare costs and improved quality of life arising from improved newborn health; reduced incidence of ADHD; improved school performance; reduced crime; and improved cardiovascular health.</td>
<td>Wolf 2015</td>
</tr>
</tbody>
</table>

**b.vii Beneficiaries**

Trees generate public and private benefits. Private property owners with trees enjoy heating and cooling savings, increased property value, and enjoyment of the amenities trees provide. Private property owners adjacent to properties with tree canopy may also enjoy these benefits without bearing the cost of the investment. Renters in buildings that benefit from trees may enjoy reduced energy costs, but may also pay higher rents that offset the cost savings. The public may enjoy benefits arising from the environmental effects of trees, including mental and physical health improvements from better air quality and enhanced amenities, moderated temperatures from reduced urban heat island effect, and existence factor of increased biodiversity.

**c. Costs of Implementation**

The cost of trees includes planting, pruning and maintenance, tree and stump removal at the end of a tree’s life, pest and disease control, irrigation, and other costs (e.g., infrastructure opportunity costs, liability costs, litter and waste disposal costs, and for public trees, inspection and administration costs)
Regional surveys of tree costs as reported by urban arborists and municipal foresters in the Piedmont (North Carolina to Texas) and Interior West (Texas west) are shown in Table 4. Austin sits on the border of these regions, so likely would experience costs somewhere within this range.

Table 5. Costs of Trees (2015$)

<table>
<thead>
<tr>
<th></th>
<th>Piedmont Region</th>
<th>Interior West Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planting (One-time)</td>
<td>$587</td>
<td>$97-$5,577</td>
</tr>
<tr>
<td>Pruning (Per tree per year, depending on size and age)</td>
<td>$0.07-$5.50</td>
<td>$4-$5,575</td>
</tr>
<tr>
<td>Pest and Disease Control (Per tree per year)</td>
<td>$23</td>
<td>N/A</td>
</tr>
<tr>
<td>Irrigation (Per year for first 5 years)</td>
<td>N/A</td>
<td>$1.14-$4.57</td>
</tr>
<tr>
<td>Removal (One-time, per inch of diameter)</td>
<td>$41-$260</td>
<td>$25-$40</td>
</tr>
</tbody>
</table>

Sources: a Vargas et. al. 2007; b McPherson et al. 2006

2. Green Roofs
   a. Biophysical Benefits

Green roofs cover building rooftops with a vegetated surface and substrate, taking the form of an “intensive” or “extensive” design. Intensive green roofs are often designed with diverse vegetation types, including trees, whereas extensive green roofs are often planted with dense, low-growing vegetation in shallower substrates (Oberndorfer et al. 2007, Ahiablame et al. 2012). Green roofs can be one means of increasing vegetation cover in urban landscapes, compensating for the vegetation that was removed during construction. The biophysical benefits of green roofs center on improved stormwater management, reduced temperatures of buildings and broader urban heat islands, and enhanced habitat resources and connectivity for biodiversity. Aesthetic appeal and functional space for urban residents are also possible, depending on design and characteristics (Oberndorfer et al. 2007).

a.i Stormwater Management

The stormwater management benefits of green roofs have been explored in a wide variety of climates and contexts. Research indicates that green roofs can retain 20-100 percent of rainfall, but this is highly dependent on the amount of rainfall and the existing water holding capacity of the roof during a given storm (reviewed in Ahiablame et al. 2012). In general, green infrastructure such as green roofs, bioretention, and porous pavements experience saturation and therefore provide little benefit in large storms and flash flood events. Studies in Austin and in locations with similar humid subtropical climates...
climates (Cfa) demonstrate that green roofs can retain 44-48 percent of rainfall volume during large (e.g., 3-inch) storms and 86-88 percent during smaller (e.g., <1-inch) storms (Carter et al. 2007, Simmons et al. 2013). One study in Maryland, USA found that per-storm retention rates varied depending on storm size, but 74 percent of the total rainfall volume over 10 months was retained by the green roof (Glass 2007). The effects of green roofs on water quality, however, are less clear, with studies showing mixed results for green roofs in removing nutrients and metals from stormwater (Ahiablame et al. 2012). However, one review suggests that as green roofs get older, their performance improves in terms of reducing pollutant loads (Rowe 2011).

a.ii Urban Heat Island Mitigation

Studies conducted at multiple spatial scales suggest that green roofs can contribute substantially to reducing urban heat island effects by increasing the albedo of existing rooftops and increasing the amount of vegetation that provides shade and cooling benefits of evapotranspiration. A modeling study of cities across the globe, including one city in a humid subtropical climate (Hong Kong), found that the maximum roof surface temperature difference for a green roof (compared to a non-vegetated roof) was 45°F cooler on a hot summer day (Alexandri and Jones 2008). Models also indicate that green roofs can reduce average ambient temperatures by up to 2.7-5.4°F when applied more broadly across an urban landscape (Meek et al. 2014, Santamouris 2014). It is important to note that the green roofs on taller buildings may contribute negligible benefits for mitigating broader urban heat island effects (Santamouris 2014). However, the cooling benefits for underlying buildings can translate to reduced air conditioning needs, leading to energy savings and reduced greenhouse gas emissions at power plants as a result (Rowe 2011).

a.iii Air Pollution Removal

Additional biophysical benefits provided by green roofs include reduction of noise and air pollution in urban streetscapes (Van Renterghem and Botteldooren 2009, Rowe 2011). Green roofs are capable of removing air pollutants from the atmosphere and acting as a carbon sink, depending on plant characteristics and design (Currie et al. 2008, Pugh et al. 2012, Rowe 2011). In addition, the cooling benefits of green roofs may contribute to reduced formation of ground-level ozone (Rowe 2011).
Research in recent years has demonstrated that green roofs support a surprising diversity of invertebrate species, including native pollinators and specialist species (Colla et al. 2009, Tonietto et al. 2011, Madre et al. 2013). Moreover, green roofs can be important “stepping stones” between urban habitat patches and contribute to functional connectivity for some species (Braaker et al. 2014). Several studies have shown that invertebrates respond to green roof habitat regardless of the broader landscape context, which suggests that even small green roofs in highly urbanized surroundings can provide important habitat value for biodiversity (Madre et al. 2013, Tonietto et al. 2011).

<table>
<thead>
<tr>
<th>Ecosystem Service Type</th>
<th>Range of Estimated Biophysical Benefits in Austin, Texas</th>
<th>References</th>
</tr>
</thead>
</table>
| Microclimate regulation and mitigation of urban heat island effects | On a per-roof basis: maximum temperature reduction of 45-54°F for roof surface temperatures (compared to non-vegetated roofs)  
|                 | At broader scales: 1.6-5.4°F reduction in ambient air temperatures with widespread green roof implementation               | Alexandri & Jones 2008, Susca et al. 2011, Santamouris 2014, Meek et al. 2014                    |
| Carbon storage and sequestration                             | Storage: 0-67.7 kg C/m² depending on plant type, substrate, and age of roof                                             | Getter et al. 2009, Whittinghill et al. 2014                                                    |
Table 6. Range of Estimated Biophysical Benefits for Green Roofs in Austin, Texas

<table>
<thead>
<tr>
<th>Benefit Category</th>
<th>Effect Size and Duration</th>
<th>Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air pollutant removal</td>
<td>Per unit area: 85 kg of pollutants removed per hectare of green roof per year (8.5 g/m²), with 0.65-1.01 g SO₂/m², 2.33-3.57 g NOₓ/m², 1.12-2.16 g PM₁₀/m², 4.49-7.17 g O₃/m². At broader scales: Up to 2046 metric tons of pollutants removed per year for widespread green roof implementation</td>
<td>Yang et al. 2008, Currie et al. 2008</td>
</tr>
<tr>
<td>Water filtration</td>
<td>Mixed results for water quality. Although total concentrations may be higher in effluent, the total loads are lower due to high runoff volume retention.</td>
<td>Rowe et al. 2011, Ahiablame et al. 2012</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>Green roofs can provide habitat for a relatively high diversity of invertebrate species, including native pollinators, and increase functional connectivity for these species</td>
<td>Colla et al. 2009, Tonietto et al. 2011, Madre et al. 2013, Braaker et al. 2014</td>
</tr>
<tr>
<td>Human well-being</td>
<td>Potential to reduce noise pollution and provide green views to building occupants</td>
<td>Van Renterghem &amp; Botteldooren 2009, Oberndorfer 2007</td>
</tr>
</tbody>
</table>

b. Economic Benefits

Green roofs provide building owners with private costs savings and increased property values. They also provide a variety of public benefits, some of which are quantifiable and some are not, especially at the scale of an individual green roof. In general, in areas that experience droughts, maintenance costs for vegetation can increase due to additional water requirements and the potential replacement of vegetation.

b.i Building Cost Savings

Green roof experts suggest that the lifespan of a roof can double under a green roof, reducing maintenance costs over conventional roofs and leading to a potential $25 per square foot savings. Additional savings to the building owner may come from incentives or development credits offered by the City. In the City of Austin, Green Roofs qualify for meeting development requisits and may qualify a development for a density bonus in the downtown area (City of Austin 2014).

b.ii Energy Costs

The insulating effect of the green roof depends on the characteristics of the building it sits on, and the climate where the building is located. In the absence of specific building data, green roof experts
suggest the insulative properties of a green roof provide approximately the equivalent of an inch of conventional insulating materials, which typically cost approximately $3 per square foot. Based on these cost savings in addition to reduced periodic repair costs, the building owner may enjoy a cost savings of $32 per square foot over a conventional roof (Breuning No Date). The relative energy savings benefit is greatest for one- and two-story buildings. Multi-story buildings experience energy efficiency improvements only on the few stories below the green roof: floors greater than four stories below the green roof are not impacted (Blackhurst et al. 2010).

b.iii Property Values

Green buildings and green roofs have been shown to increase property values. One analysis showed the real estate effect nationally at $13 per square foot of green roof (GSA 2011). Buildings that have views of a green roof experience increases in value as well. A study in New York City found that apartment rents in buildings with green roofs were about 16 percent higher on average than buildings without green roofs (Ichihara and Cohen 2010). Data from national surveys by the U.S. Green Building Council found that green buildings in general realize 5.7 percent more rent than conventional buildings (GSA 2011).

b.iv Stormwater Runoff Cost

Modeling results suggest that most green roofs reduce annual stormwater runoff volume. This reduces the stormwater management costs to the city, and may reduce the need for future conventional stormwater infrastructure investments. An individual green roof may not have a measurable effect on public stormwater investment requirements, however more widespread adoption has been shown to produce substantial public savings. In Washington, D.C., a 10 percent increase in green roof coverage could reduce the infrastructure costs in the District’s Long-Term Control Plan (LTCP) by $10 million (Deutsch et al. 2005). In Detroit, a 10 percent increase in green roof coverage could reduce the LTCP costs by $114 million (Deutsch et al. 2005).

b.v Air Quality

Green roofs also provide public economic benefits by improving air quality. The most commonly measured pollutant reductions are nitrogen-oxides and particulate matter. The GSA (2011) calculated that the economic benefit of reducing these pollutants is negligible to almost $0.60 per square foot of
green roof. For an individual green roof, this does not add up to a huge benefit, but at a larger scale, the economic benefits become more meaningful.

b.vi Health and Well-Being

The improvements in human health and well-being that arise from access and views of greenspaces apply to greenroofs. A green roof that is within view of office space may improve worker productivity: one study found that workers who have a view of vegetation out their window are almost 3 percent more productive (GSA 2011). College students working in a computer lab with plants were 12 percent more productive, demonstrating faster reaction times and lower stress (Lohr et al. 1996). Benefits in the form of less stress, better mental health, and faster recovery times have also been documented for younger students, health care workers, and patients in hospitals. All of these health and well-being effects have economic implications, though they are not easy to quantify. Lower absenteeism has the potential to save employers millions per year, and the effects of reduced stress may contribute to lower health care costs nationally, and higher quality of life (Wolf 2014).

b.vii Beneficiaries

Building owners enjoy cost savings and increased property value, rental rates, and potentially increased worker productivity after installing a green roof. Renters in a building with a greenroof may experience reduced energy costs, depending on site-specific conditions, but higher rental rates may offset this benefit. The public enjoys reduced stormwater management costs, especially if green roof installation is widespread. The public may also enjoy benefits related to air quality improvement and urban heat island mitigation, and enhanced biodiversity if green roof implementation is widespread in an urban area. These public benefits are more limited with isolated green roof applications.
Table 7. Range of Estimated Values of Economic Benefits of Green Roofs in Austin, Texas

<table>
<thead>
<tr>
<th>Economic Benefit</th>
<th>Range of Values of Economic Benefits for Austin, Texas</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Cost Savings</td>
<td>May extend the life of the roof underlayment by 20 years or more.</td>
<td>EPA 2000</td>
</tr>
<tr>
<td>Development Cost Savings</td>
<td>Developers may use green roofs to meet certain development requirements or earn a density bonus credit.</td>
<td>City of Austin No Date</td>
</tr>
<tr>
<td>Energy Savings</td>
<td>Expected reduction in energy demand and cost. Magnitude dependent on existing energy efficiency of the building and properties of the green roof. Buildings that are already well-insulated likely will experience more limited energy benefits. Energy savings are greatest for the first floor below the roof, with decreasing benefits up to four stories below the roof.</td>
<td>Blackhurst et al. 2010</td>
</tr>
<tr>
<td>Carbon Sequestration</td>
<td>$44-$239 per metric ton of Carbon</td>
<td>Interagency Working Group 2016</td>
</tr>
<tr>
<td>Nitrogen Dioxide Removal</td>
<td>$0.13-$0.33 per kg</td>
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</tr>
<tr>
<td>Small Particulate Matter</td>
<td>$0.04-$0.09 per kg</td>
<td>Nowak et al. 2016</td>
</tr>
<tr>
<td>Avoided Stormwater Runoff Costs to City of Austin</td>
<td>$2 per cubic foot of stormwater diverted from system</td>
<td>American Forests 2002</td>
</tr>
<tr>
<td>Avoided Stormwater Runoff Fee Assessed to Property Owners</td>
<td>Up to a 72% reduction in the monthly drainage charge assessed by the City of Austin. Actual savings depends on site-specific factors.</td>
<td></td>
</tr>
<tr>
<td>Impacts on Property Values</td>
<td>Up to 6% increase in rental rates, which may increase property values</td>
<td>GSA 2011</td>
</tr>
<tr>
<td>Avoided Costs of Ecological and Species Habitat Management</td>
<td>Unquantifiable, but likely positive. Higher value for positive effects on habitat for sensitive species</td>
<td></td>
</tr>
<tr>
<td>Avoided Health Care Costs, Improved Human Well-being</td>
<td>Unquantifiable, but likely positive if green roof is within view or accessible. Positive relationships have been measured at a national scale, attributing benefits of access to green space to reduced healthcare costs and improved quality of life arising from improved newborn health; reduced incidence of ADHD; improved school performance; reduced crime; and improved cardiovascular health.</td>
<td>Wolf 2015</td>
</tr>
</tbody>
</table>

c. Costs of Implementation

Installation costs of an extensive green roof may be between around $10 and $30 per square foot more expensive than conventional roofs (Breuning No Date; GSA 2011; Center for Neighborhood Technology No Date), but typically the extra cost for extensive roofs is on the lower end of this range. Over its lifetime, a green roof will require maintenance of around $15 per square foot (Breuning No Date): annual
maintenance is typically higher than a conventional roof by $0.21 to $0.31 per square foot (GSA 2011). The Center for Neighborhood Technology (No Date) suggests maintenance costs for green roofs range from 2 cents per square foot to around 40 cents. The maintenance cost is influenced by roof design and local climate. Table 3 summarizes the construction and maintenance costs, as compiled by the Center for Neighborhood Technology.

Table 8. Costs of Green Roofs

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Extensive</td>
<td>$7.38</td>
<td>$342.55</td>
</tr>
<tr>
<td>Intensive</td>
<td>$16.86</td>
<td>$550.19</td>
</tr>
</tbody>
</table>

Source: 1 Grey et al. 2013; 2 Center for Neighborhood Technology, No Date.

3. **Bioretention, Biofiltration Systems, and Rain Gardens**

   **a. Biophysical Benefits**

   Bioretention, biofiltration systems, and rain gardens are typically small depressions that retain and treat stormwater runoff with plants and soils. Generally, the terms “bioretention cells” and “rain gardens” describe stormwater management systems that are designed to function similarly to natural landscapes by capturing runoff and promoting infiltration/filtration via vegetated systems planted in a variety of media types (Ahiablame et al. 2012). Bioretention cells and rain gardens may or may not be designed with an underdrain, depending on underlying soil conditions. The City of Austin’s definition of a “biofiltration” system requires a two-step process, in which runoff is first directed to a sedimentation basin for pre-treatment and then directed through a cell with a biologically active system of plants rooted in a filter medium (City of Austin 2016, Section C). The majority of research conducted thus far has focused on bioretention systems without pre-treatment sedimentation basins. The biophysical benefits provided by these types of system include reduced urban runoff, improved water quality, microclimate regulation, reduced air pollution and noise, and support for urban biodiversity.

   Bioretention systems perform particularly well in reducing runoff volumes and peak flow rates and can capture the entire inflow volume, especially in small events. In general, green infrastructure such as green roofs, bioretention, and porous pavements experience saturation and therefore provide little benefit in large storms and flash flood events. A 7-month field study in a humid subtropical climate (Virginia, USA) documented a cumulative volume reduction of 97 percent during the study period; on a
per-storm basis, the median volume reduction was 100 percent, with only 5 of 28 storm events producing outflow (DeBusk and Wynn 2011). Six bioretention cells monitored in Maryland and North Carolina, USA (both humid subtropical climates) for more than 10 months also performed well, with median runoff volume reduction ranging from 40-99 percent across the six sites (Li et al. 2009). A nationwide modeling study with 3-year continuous simulations for real precipitation patterns demonstrated that individual rain gardens in Texas could reduce total runoff volumes by 65 percent (Jennings 2016).

The reduction in runoff volumes also translates into reduction of peak flow rates, with one study in North Carolina, USA documenting a mean peak flow reduction of 99 percent over a two-year time span (Hunt et al. 2008). Modeling studies demonstrate that when bioretention systems and/or rain gardens are implemented broadly across a watershed, they can cumulatively contribute to increased groundwater recharge, increased stream baseflow rates, and reduced number of erosive events in urban streams, which can in turn lead to improved stream ecological health (Hamel et al. 2013, Glick et al. 2016). The in-stream ecological effects of catchment-scale implementation of green infrastructure have been monitored in an innovative Australian study, although no change in ecological indicators has been observed thus far (Walsh et al. 2015).

The performance of bioretention systems in removing pollutants from urban runoff has also been relatively well documented. A lab study conducted with synthetic and real stormwater in Austin, Texas demonstrated that vegetated systems in biofiltration media removed all nutrients (especially total phosphorus, >80 percent removed), metals (>95 percent removed for copper, lead, and zinc), and total suspended solids (>85 percent removed) (Limouzin et al. 2011). A separate study in Austin, Texas indicated that effluent from biofiltration systems had concentrations of total suspended solids, zinc, and *E. coli* that were significantly lower than those of runoff from undeveloped land in Austin (Richter 2015). In general, these results agree with data reported from other studies, with bioretention systems in a variety of settings showing consistently high removal rates for total suspended solids, some nutrients, and metals (although removal rates are dependent upon design characteristics) (reviewed in Ahiablame et al. 2012). Recent studies have also demonstrated bioretention systems can effectively remove *E. coli* over the long-term (70-97 percent removal, in lab experiments conducted by Zhang et al. 2011).
As with other small vegetated areas in urban landscapes, rain gardens and bioretention systems can also store and sequester carbon, mitigate urban heat island effects, reduce noise pollution, and support urban biodiversity. Even small areas of herbaceous cover can store 0.14 kg carbon per square meter (Davies et al. 2011), which can increase substantially as the system ages (i.e., 3.34 kg carbon per square meter after 21 years; Bouchard et al. 2013). In addition, small vegetated areas contribute to overall cooling effects through transpiration (Perring et al. 2013, Davis et al. 2016) and can reduce noise levels in urban areas (Bolund and Hunhammar 1999). Furthermore, a series of studies in Melbourne, Australia demonstrated that bioretention systems support high biodiversity invertebrate species, with greater species richness in bioretention basins than in nearby urban green spaces (Kazemi et al. 2009, Kazemi et al. 2011).

Table 9. Range of Estimated Biophysical Benefits for Bioretention, Biofiltration Systems, and Rain Gardens in Austin, Texas

<table>
<thead>
<tr>
<th>Ecosystem Service Type</th>
<th>Range of Estimated Biophysical Benefits in Austin, Texas</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microclimate regulation and mitigation of urban heat island effects</td>
<td>Some potential for minor cooling effects (as with any small vegetated area)</td>
<td>Perring et al. 2016, Davis et al. 2016</td>
</tr>
</tbody>
</table>
| Carbon storage and sequestration                | **Storage:** 0-3.34 kg C/m²  
**Sequestration:** 0.05-0.09 kg C/m² per year                                                                         | Bouchard et al. 2013, Davies et al. 2011                                     |
| Air pollutant removal                           | No estimates in literature; however, the cooling effects of vegetation can contribute to reduced ozone formation           | Perring et al. 2013                                                         |
| Stormwater retention and runoff reduction       | **On a per-site basis:** 40-100% of rainfall volume retained per storm and 58-97% of rainfall volume retained annually.  
| Water filtration                                | **Concentration reduction:** significant reduction in total suspended solids (mg/L) likely (85-95% removal)  
**Pollutant load reduction:** 30-50% reduction in load for total suspended solids, total phosphorus, total nitrogen, fecal coliform, and total zinc with widespread implementation (conservative estimate) | Geosyntec 2016, International BMP Database 2014, Richter et al. 2015, Limouzin et al. 2011 |
| Biodiversity                                    | Bioretention systems and rain gardens support similar or greater diversity of invertebrates than nearby green spaces. With widespread implementation, they can also contribute to improved ecological health and aquatic life in urban streams. | Kazemi et al. 2009, Kazemi et al. 2011, Glick et al. 2016, Hamel et al. 2013, Walsh et al. 2015 |
| Human well-being                                | Some potential to provide residents with increased exposure to nature and associated health benefits (as with other vegetated areas) | Sandifer et al. 2015                                                        |
b. **Economic Benefits**

b.i **Stormwater**

The City of Austin charges property owners a Drainage Utility Fee (DUF) for managing stormwater. The DUF includes a base rate applied to the square footage of a property’s impervious area, modified by an adjustment factor. The median household charge is approximately $12 per month (Pantalion, 2016). Biofiltration controls can help reduce stormwater volumes that flow into the City of Austin’s stormwater infrastructure, and help property owners qualify for MDC discounts. Monthly discounts range from $0.22 for a 55-gallon reduction in stormwater volume, up to $8.05 per month for reductions of 3,000 gallons or more. These discounts reflect reduced costs to the City of Austin of managing and treating stormwater (Pantalion, 2016). Bioretention and related stormwater controls help reduce runoff volumes, which can help reduce stormwater management costs.

b.ii **Carbon Sequestration and Air Quality**

Bioretention areas that include significant vegetation, including grasses, shrubs, and trees produce environmental benefits ranging from air quality improvements to carbon sequestration. These benefits would be valued using the economic values and methods described above for trees. Shrubs and grasses and other smaller vegetation has smaller effects on these ecosystem services than do trees, so biofiltration that does not include trees would produce a smaller magnitude of these benefits.

b.iii **Beneficiaries**

Bioretention structures and rain gardens generate benefits for a range of stakeholders. City of Austin stormwater managers benefit through reduced volumes of stormwater managed and processed. Reducing stormwater volumes can also help reduce demand for stormwater services as the city’s population grows, thus extending the capacity of the city’s stormwater infrastructure further out into the future. Combined, these benefits can reduce operating costs. Property owners benefit through reduced MDC costs. Property owners also incur the costs of implementing the green infrastructure controls, which we address in the next subsection. Residents of multi-family and other rental properties may or may not benefit from reduced MDC costs, depending on their agreements with property owners regarding utility payments. In cases where property owners, not tenants, pay stormwater utility fees, owners may or may not pass reduced MDC costs on to tenants. To the extent that stormwater controls
help reduce flooding, they can also help reduce downstream flood risks, damage and costs. These benefits accrue to downstream property owners and to the City of Austin through reduced emergency management and response costs. The carbon sequestration benefits accrue to society at large.

Table 10. Range of Estimated Values of Economic Benefits of Bioretention, Biofiltration Systems, and Rain Gardens in Austin, Texas

<table>
<thead>
<tr>
<th>Economic Benefit</th>
<th>Range of Values of Economic Benefits for Austin, Texas</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Costs</td>
<td>Unlikely to have significant effect; however, installations with trees, water features, or in areas with considerable influence on a building may generate minor energy cost savings, especially if density of installations is high in an otherwise hardscape-dominated area.</td>
<td></td>
</tr>
<tr>
<td>Carbon Sequestration</td>
<td>$44-$239 per metric ton of Carbon</td>
<td>Interagency Working Group 2016</td>
</tr>
<tr>
<td>Avoided Stormwater Runoff Costs to City of Austin</td>
<td>$2 per cubic foot of stormwater diverted from system</td>
<td>American Forests 2002</td>
</tr>
<tr>
<td>Avoided Stormwater Runoff Fee Assessed to Property Owners</td>
<td>Up to a 72% reduction in the monthly drainage charge assessed by the City of Austin. Actual savings depends on site-specific factors.</td>
<td></td>
</tr>
<tr>
<td>Impacts on Property and Amenity Values</td>
<td>Evidence of increase in property value is limited, with some studies showing potential negative effect and others positive. Expected benefit associated with well-maintained installations that add curb appeal beyond typical landscaping.</td>
<td></td>
</tr>
<tr>
<td>Avoided Costs of Ecological and Species Habitat Management</td>
<td>Unquantifiable, but likely positive. Higher value for positive effects on habitat for sensitive species</td>
<td></td>
</tr>
<tr>
<td>Avoided Health Care Costs, Improved Human Well-being</td>
<td>Unquantifiable, but positive relationships have been measured at a national scale, attributing benefits of access to green space to reduced healthcare costs and improved quality of life arising from improved newborn health; reduced incidence of ADHD; improved school performance; reduced crime; and improved cardiovascular health.</td>
<td>Wolf 2015</td>
</tr>
</tbody>
</table>

Costs of implementing bioretention and rain garden stormwater controls can be very site specific depending on local soil, vegetation, and climate conditions. Tables 11A and 11B summarize the installation and maintenance and management cost information reported in the literature. The “Low” construction costs apply to smaller scale and self-installed controls. In Table 11A, installation costs for biofiltration and rain gardens reported as cost per cubic foot of stormwater retention volume. Costs for
vegetative filter strip reported per square foot of installation. O&M costs reports as annual average costs per instillation. Costs in Table 11B report per square foot of instillation.

Table 11A: City of Austin Costs for Bioretention and Rain Garden Structures (2016$)

<table>
<thead>
<tr>
<th></th>
<th>Low Cost</th>
<th>Average Cost</th>
<th>High Cost</th>
<th>Annual O&amp;M/Instillation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biofiltration ($/CF)</td>
<td>$5.14</td>
<td>$11.33</td>
<td>$18.05</td>
<td>$3,000</td>
</tr>
<tr>
<td>Rain Garden ($/CF)</td>
<td>$8.21</td>
<td>$24.25</td>
<td>$61.79</td>
<td>$1,700</td>
</tr>
<tr>
<td>Vegetative Filter Strip ($/SF)</td>
<td>$1.98</td>
<td>$3.11</td>
<td>$4.80</td>
<td>$3,076</td>
</tr>
</tbody>
</table>

Source: City of Austin staff, Personal Communication, January 17, 2017.

Table 11B: Nationwide Range of Costs for Bioretention and Rain Garden Structures (2016$)

<table>
<thead>
<tr>
<th>Costs/Sq. Ft.</th>
<th>Maintenance Costs/Sq. Ft.</th>
<th>Useful Lifespan (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>$5.943</td>
<td>$0.380</td>
</tr>
<tr>
<td>Medium</td>
<td>$7.805</td>
<td>$0.488</td>
</tr>
<tr>
<td>High</td>
<td>$18.522</td>
<td>$0.747</td>
</tr>
</tbody>
</table>

Source: (Center for Neighborhood Technology, No date)

Table 12. Costs of Bioretention, Biofiltration Systems, and Rain Gardens Used in Analysis

<table>
<thead>
<tr>
<th>Costs/Cubic Foot</th>
<th>Low</th>
<th>High</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biofiltration</td>
<td>$5.14</td>
<td>$18.05</td>
<td>$0.38</td>
<td>$0.747</td>
</tr>
<tr>
<td>Rain Garden</td>
<td>$8.21</td>
<td>$61.79</td>
<td>$0.38</td>
<td>$0.747</td>
</tr>
<tr>
<td>Vegetative Filter Strip</td>
<td>$1.98</td>
<td>$4.80</td>
<td>$0.38</td>
<td>$0.747</td>
</tr>
</tbody>
</table>

Source: *City of Austin; * Center for Neighborhood Technology, No Date.

A subdivision in Austin included four bioretention areas as a substitute for the sedimentation-filtration pond that would have otherwise been required. In addition to providing the ecosystem services benefits and values described above, installing the bioretention structures cost approximately $185,000 less. On a per-lot basis, the bioretention option cost approximately $450, compared to approximately $1,700 for the sedimentation-filtration option. (US EPA, 2005)
4. Green Façade

a. Biophysical Benefits

The term “green façade” or “green wall” describes built vertical surfaces that support vegetation. Green façades may be “direct,” with vegetation growing directly on a wall itself, or “double-skin,” which support plants with engineered structures such as cables and create an insulating layer of air between plants and building (Hunter et al. 2012, Perini et al. 2011). In both cases, the plants are rooted in soil at the ground level or in planter boxes. “Living walls,” on the other hand, include encased growing medium within a support structure that is anchored on the building surface (i.e., plants need not be rooted in substrate at the base of the wall) (Perini et al. 2011). The biophysical benefits of green façades center on microclimate regulation, noise reduction, and air pollutant capture.

Vegetation adjacent to building walls can contribute substantially to urban microclimates by screening solar radiation before it reaches the building, increasing albedo (reflective capacity), and cooling the surrounding air as plants transpire (Hunter et al. 2012). The cooling benefits can be especially pronounced for green façade designs that maintain an insulating layer between the building surface and vegetation. Studies in humid subtropical climates indicate that building surface temperatures behind vegetated walls can be 21-36°F cooler than non-vegetated walls on hot sunny days (Alexandri and Jones 2008, Chen et al. 2013, Mazzali et al. 2013), which in turn leads to reduced energy loads for building climate control. Furthermore, the temperature effects can extend to the adjacent street “canyons,” reducing air temperatures by around 7°F (Alexandri and Jones 2008). The cooling benefits vary with individual plant species characteristics, including physiology and leaf area (Cameron et al. 2014).

Vegetated walls can also provide air quality benefits in urban landscapes, including capture of particulate matter and uptake of O₃, NOₓ, and SO₂ (Currie et al. 2008, Pugh et al. 2012). The cooling benefits they provide can also reduce formation of ground-level O₃. The vegetation in green façades also reduce noise pollution and act as sound insulation tools for buildings (Azkorra et al. 2015).

In addition, vegetated walls can be designed specifically to provide foraging or nesting resources for local wildlife species (Francis 2011). They show promise for supporting arthropod species (i.e., beetles...
and spiders) and urban bird species (i.e., house sparrows and European starlings) (Chiquet et a. 2013, Madre et al. 2015).

Table 13. Range of Estimated Biophysical Benefits for Vegetated Walls in Austin, Texas

<table>
<thead>
<tr>
<th>Ecosystem Service Type</th>
<th>Range of Estimated Biophysical Benefits in Austin, Texas</th>
<th>References</th>
</tr>
</thead>
</table>
| Microclimate regulation and mitigation of urban heat island effects | On a per-wall basis: maximum temperature reduction of 16-36°F for wall surface temperatures (compared to non-vegetated walls)  
At broader scales: 5.4-7.2°F reduction in ambient air temperatures with widespread vegetated wall implementation | Alexandri & Jones 2008, Mazzali et al. 2013, Perez et al. 2011, Cameron et al. 2014, Chen et al. 2013 |
| Carbon storage and sequestration                           | Likely storage of < 1.0 kg C/m² for non-woody vegetation and 6.7 – 16.03 kg C/ m² for woody vegetation                  | Davies et al. 2011                  |
| Air pollutant removal                                      | At broad scales: Up to 3,300 kg pollutants removed per year (and concentration reductions of 6-62% possible) with widespread implementation. Annual removal estimates per pollutant include 620 kg NO₂, 1090 kg O₃, 1370 kg PM₁₀, and 230 kg SO₂. | Currie et al. 2008, Pugh et al. 2012 |
| Stormwater retention and runoff reduction                 | No estimates in the literature; very little contribution to stormwater retention expected                               |                                     |
| Water filtration                                           | No estimates in the literature; very little benefit to water filtration expected                                       |                                     |
| Biodiversity                                               | Vegetated walls can provide some resources for invertebrates and urban birds                                       | Madre et al. 2015, Chiquet et al. 2013 |
| Human well-being                                          | Can reduce noise pollution, provide sound insulation for buildings, and provide green views to residents            | Azkorra et al. 2015                 |

b. Economic Benefits

The economic benefits of green walls have not been studied as extensively as green roofs. They provide similar types of benefits, but from the literature available to date, the magnitude of benefits appears to be smaller, and costs higher. However, for taller buildings, some studies have suggested that green walls be used in conjunction with or instead of green roofs to produce maximum economic benefits. For example, the GSA found that “Simultaneous use of green roofs and green walls is significantly more effective than the use of green roofs alone in reducing surface and ambient air temperatures in urban canyons and over rooftops.” (GSA 2011 pg. 34)

Green walls generate both public and private benefits. Economic benefits to the building owner arise from the insulating and protective properties of the wall system: the vegetation can reduce energy demand for heating and cooling and increases the lifespan of the exterior façade, increasing the time
between required maintenance. Green walls also provide aesthetic benefits that may increase the property value or rent a building owner may charge. The performance and associated economic benefits of green walls depends in part on choosing vegetation appropriate for the local climate conditions. Using vegetation not suited to the climate may increase costs associated with additional maintenance and irrigation.

Much of the economic research on green wall systems comes from Europe. One study looked at the benefits and costs of several theoretical green wall installations in Genoa, Italy (Perini 2013). This study found the green wall could increase property value by 2 to 5 percent, with the highest increase for buildings located in the periphery of the city. Energy savings in the Mediterranean climate where the hypothetical building would be located resulted from reduced air conditioning. Maximum benefit depended on the existing insulation of the building, with all concrete-walls benefiting the most (up to 65.8 percent), and walls with polystyrene insulation already in place benefiting the least (1.4 to 2.6 percent energy use reduction). The green wall systems also increased the lifespan of the building façade (plaster) from 35 years to 50 years. The study examined the literature on social benefits (e.g., air quality improvement, urban heat island effect, and biodiversity) but found limited data to support the quantification of benefits on a single-building scale. Overall, the study found that green wall systems with the lowest installation cost (green walls versus living walls) had a positive rate of return to the building owner, but in no scenario, did the living wall system produce positive net benefits because of its ongoing maintenance costs.

Another benefit-cost analysis of a living wall system on a school in Dubai found that the system produced a yearly cooling savings of 18 percent, and an increased rental rate (Haggag and Hassan 2015). However, with these quantified benefits, the payback period for the building owner would be 17 years under current energy prices. This study did not consider other private benefits, such as increased longevity of the building façade or public benefits, such as air quality improvement.

The public benefits discussed but not quantified in the economic literature include reduced urban heat island effect, improved exterior air quality (green walls installed indoors can improve interior air quality as well), aesthetic improvements, biodiversity, and noise reduction (Green Roofs for Healthy Cities 2008). Stormwater capture is rarely mentioned as a benefit of green walls, but some specifically designed examples do exist (see e.g., City of Portland 2014).
Table 14. Range of Estimated Values of Economic Benefits of Vegetated Walls in Austin, Texas

<table>
<thead>
<tr>
<th>Economic Benefit</th>
<th>Range of Values of Economic Benefits for Austin, Texas</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Cost Savings</td>
<td>Depends on façade material, but may reduce maintenance requirements and extend the life of the building façade.</td>
<td>Perini 2013</td>
</tr>
<tr>
<td>Energy Costs</td>
<td>Expected reduction in energy demand and cost, largely dependent on existing insulation quality. Buildings that are already well-insulated likely will experience more limited energy benefits.</td>
<td>Hassan 2015</td>
</tr>
<tr>
<td>Carbon Sequestration</td>
<td>$44-$239 per metric ton of Carbon</td>
<td>Interagency Working Group 2016</td>
</tr>
<tr>
<td>Nitrogen Dioxide Removal</td>
<td>$0.13-$0.33 per kg</td>
<td>Nowak et al. 2016</td>
</tr>
<tr>
<td>Sulfur Dioxide Removal</td>
<td>$0.04-$0.09 per kg</td>
<td>Nowak et al. 2016</td>
</tr>
<tr>
<td>Small Particulate Matter</td>
<td>$26.45-$66.14 per kg</td>
<td>American Forests 2002</td>
</tr>
<tr>
<td>Impacts on Property and Amenity Values</td>
<td>Likely positive, for the same reason green roofs and street trees provide benefits. May affect the value of the building it's installed on, as well as adjacent buildings with views of the green façade.</td>
<td></td>
</tr>
<tr>
<td>Avoided Costs of Ecological and Species Habitat Management</td>
<td>Unquantifiable, but likely insignificant, because habitat provided by vegetated walls is typically not suitable for sensitive species, and does not offer habitat types that are considered scarce, even in an urban environment.</td>
<td></td>
</tr>
<tr>
<td>Avoided Health Care Costs, Improved Human Well-being</td>
<td>Unquantifiable, but positive relationships have been measured at a national scale, attributing benefits of access to green space to reduced healthcare costs and improved quality of life arising from improved newborn health; reduced incidence of ADHD; improved school performance; reduced crime; and improved cardiovascular health.</td>
<td>Wolf 2015</td>
</tr>
</tbody>
</table>

b.i Beneficiaries

Building owners and occupants are the primary beneficiary of green walls, with some aesthetic benefit accruing to pedestrians and adjacent property owners in view of the green wall installation. Most of the public benefits associated with individual green walls are too small to make a noticeable difference in factors such as the urban heat island and air quality. However, the incremental improvement of individual installations could add up if green walls are more widely adopted, leading to measurable public benefits.
c. Costs of Implementation

Green wall systems vary in installation costs, depending on their design. Livings walls are typically more expensive to install and maintain than green façades using ground-level plantings. Installation costs can range from approximately $80 to $150 per square foot for livings walls (Liang 2014). Maintenance costs for living walls can range from $7 to $15 per square foot. Installation for green façades can range from $25 to $40 per square foot or more, which includes installation of the climbing structure, substrate, plants, and irrigation systems (Architek No Date; State of Victoria 2014; Perini and Rosasco 2013). Annual maintenance costs for green façades are not widely documented in the literature but are typically cited as minimal ($0.25 to $1 per square foot, Perini and Rosasco 2013). Typical activities, such as pruning, plant replacement if necessary, and debris clearing are often covered in landscape budgets. Other activities, such as structural inspection, occur infrequently, if at all. Maintenance costs are higher for green wall systems in climates that require irrigation, because water charges would accrue, and the irrigation system would need additional annual maintenance and repair. These are still fairly new systems, and engineering challenges in installation and maintenance remain for many applications. Costs may decline as green walls gain wider acceptance, as was the case for green roofs (Rizer 2014).

Table 15. Costs of Vegetated Walls

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Living Walls</td>
<td>$80</td>
<td>$150</td>
</tr>
<tr>
<td>Green Facades</td>
<td>$25</td>
<td>$40</td>
</tr>
</tbody>
</table>

Sources: Liang 2014, Architek No Date; State of Victoria 2014; Perini and Rosasco 2013

5. Porous Pavement

a. Biophysical Benefits

Porous pavement promotes retention of stormwater by allowing water to permeate the surface layer and infiltrate into underlying substrate, which can in turn reduce pollutants and recharge groundwater. A variety of porous pavement systems exist, including permeable interlocking concrete pavers, concrete grid pavers, open-jointed block pavement, and porous asphalt. In some types of porous pavement, vegetation can grow between paving units and promote cooling through evapotranspiration.
Research on stormwater management performance indicates that porous pavements substantially reduce runoff volume and peak flow rates. Studies from humid subtropical climates in North Carolina, Florida, and Georgia, USA have demonstrated that porous pavement can reduce runoff volumes by more than 90 percent and can eliminate runoff entirely for small storms (Rushton 2001, Collins et al. 2008, Dreelin et al. 2006, Bean et al. 2007, Ball and Rankin 2010). In general, green infrastructure such as green roofs, bioretention, and porous pavements experience saturation and therefore provide little benefit in large storms and flash flood events. A modeling study for an Austin watershed demonstrated that incorporating porous pavement as part of a broader green infrastructure implementation plan could lead to reduced runoff volumes, reduced peak flow rates, increased groundwater recharge, and reduced pollutant loads, although the relative contribution of porous pavement was minor compared to other green infrastructure types (Geosyntec 2016).

Table 16. Range of Estimated Biophysical Benefits for Porous Pavement in Austin, Texas

<table>
<thead>
<tr>
<th>Ecosystem Service Type</th>
<th>Range of Estimated Biophysical Benefits in Austin, Texas</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microclimate regulation and mitigation of urban heat island effects</td>
<td>Mixed results for cooling capabilities of porous pavements in similar climates, although new-generation materials appear to have greater thermal performance.</td>
<td>Santamouris 2013, Qin 2015, Kevern et al. 2009, Stempihar et al. 2013</td>
</tr>
<tr>
<td>Carbon storage and sequestration</td>
<td>No estimates in the literature; very little carbon storage and sequestration expected</td>
<td></td>
</tr>
<tr>
<td>Air pollutant removal</td>
<td>Unlikely to have air quality benefits; however, cooling effects could reduce formation of ozone</td>
<td></td>
</tr>
</tbody>
</table>
| Stormwater retention and runoff reduction  | **On a per-site basis:** 74-100% of rainfall volume retained per storm  
**At broader spatial scales:** Some reduction in runoff volumes and peak flow | Collins et al. 2008, Dreelin et al. 2006, Hunt et al. 2008, Ball and Rankin 2010, Geosyntec 2016 |
| Water filtration                           | **Concentration reduction:** significant reduction in total suspended solids (58-94%), metals (20-99%), and total phosphorus (10-78%) (mg/L) likely  
**Pollutant load reduction:** Total pollutant loads are likely low due to high runoff volume retention. 3.4 kg/ha/year estimated for total nitrogen and 0.4 kg/ha/year estimated for total phosphorus in one study (Bean et al. 2007) | International Stormwater BMP Database 2014, Richter et al. 2015, Ahiablame et al. 2012, Bean et al. 2007 |
| Biodiversity                               | With widespread implementation, they can contribute to increased groundwater recharge and improved ecological health and aquatic life in urban streams. |                                                                            |

The benefits for water quality vary between studies, indicating that performance depends on a variety of factors related to design and precipitation. The International Stormwater BMP Database 2014
statistical summary report indicates that porous pavements are associated with statistically significant reductions in total suspended solids, total phosphorus, and some metals (copper, lead, nickel, and zinc).

Porous pavements can also provide cooling benefits but results from previous studies have been inconclusive. In general, porous pavements can have a cooling effect when the retained water evaporates; however, when the water is depleted, the pavement surface can be hotter than conventional pavements (Santamouris 2013). In addition, porous pavements generally have a lower albedo than impermeable types. Results from studies in Arizona, South Carolina, and Iowa, USA demonstrate that porous pavements can reach higher daytime surface temperatures than other pavements, but they also cool to lower temperatures overnight (Caslon et al. 2009, Haselbach 2009, Kevern et al. 2009).

b. Economic Benefits

Porous pavement generates economic benefits primarily through the stormwater retention effect, reducing the need for other types of stormwater infrastructure. These benefits are described in more detail for Austin under the Bioretention section above.

Depending on the type of material used, the porous material may cost less to install, resulting in a reduced cost of development (Century West Engineering No Date). The cost savings comes from several sources. First, on street and parking lot applications, porous pavement may eliminate the need for standard curbs, gutters, storm drains, piping, and retention basis. Second, because extensive stormwater infrastructure is not required, less land is needed to manage the stormwater (i.e., detention basis are not required) so it may be put to other uses (ConcreteNetwork.com 2017).

Porous pavement applications that would not typically require stormwater management infrastructure (i.e., sidewalks, pedestrian areas) would not likely result in similar cost savings to developers. The economic benefit for these areas would primarily be in the form of reduced public stormwater infrastructure costs and reduced flooding, as described above.

b.i Beneficiaries

For porous pavement installed on private property, the property owner would enjoy any cost savings that materializes from choosing porous pavement over conventional pavement, primarily the cost
savings that comes from reduced drainage system requirements. The public (i.e., taxpayers) would enjoy the benefits of reduced public stormwater infrastructure, if a porous pavement installation reduced the need for stormwater retention on public property.

Table 17. Range of Estimated Values of Economic Benefits of Porous Pavement in Austin, Texas

<table>
<thead>
<tr>
<th>Economic Benefit</th>
<th>Range of Values of Economic Benefits for Austin, Texas</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Cost Savings</td>
<td>May reduce cost of private stormwater management infrastructure required, such as curbs and gutters and catchment basins.</td>
<td>Century West Engineering No Date</td>
</tr>
<tr>
<td>Avoided Stormwater Runoff Costs to City of Austin</td>
<td>$2 per cubic foot of stormwater diverted from system</td>
<td>American Forests 2002</td>
</tr>
<tr>
<td>Avoided Stormwater Runoff Fee Assessed to Property Owners</td>
<td>Up to a 72% reduction in the monthly drainage charge assessed by the City of Austin. Actual savings depends on site-specific factors, and demonstration that installation meets design criteria.</td>
<td></td>
</tr>
<tr>
<td>Avoided Costs of Ecological and Species Habitat Management</td>
<td>Unquantifiable, but likely positive. Higher value for positive effects on habitat for sensitive species</td>
<td></td>
</tr>
</tbody>
</table>

c. Costs of Implementation

Tables 18 shows the costs of instillation and O&M for porous pavement in City of Austin.

Table 18. Costs of Porous Pavement

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous Pavement</td>
<td>Low: $6.34</td>
<td>High: $18.55</td>
</tr>
</tbody>
</table>

Source: ¹ City of Austin; ² Center for Neighborhood Technology, No Date.

Porous materials are even more cost competitive in larger applications and for areas where conventional alternatives would require stormwater retention infrastructure.

6. Cisterns

a. Biophysical Benefits

A cistern is an above- or below-ground tank that collects and stores rainwater for reuse. The biophysical benefits of cisterns include reducing stormwater volume and peak flow rates, which can in turn contribute to improved ecological health of urban streams. In addition, the water collected in a cistern can be reused for landscape purposes, which reduces the need for potable water in irrigation. Two
Austin-based modeling studies included cisterns as part of broader green infrastructure implementation scenarios and demonstrated that cisterns could play a substantial role in reducing peak flow rates and total runoff volumes in Austin watersheds (Glick et al. 2016, Geosyntec 2016). In most urban landscapes, a multi-pronged strategy of stormwater harvesting (e.g., with cisterns) combined with infiltration (e.g., with biofiltration) will be required to achieve stormwater targets and improve urban stream health (Askari et al. 2015, Burns et al. 2015). The stormwater management benefits of cisterns can be an important strategy to reduce the “flashiness” of flow in urban streams and lead to improvements in stream health, including reduced flooding, reduced erosion, and improved aquatic life. Cisterns would need to be emptied prior to large storage events to provide additional storage.

Table 19. Range of Estimated Biophysical Benefits for Cisterns in Austin, Texas

<table>
<thead>
<tr>
<th>Ecosystem Service Type</th>
<th>Range of Estimated Biophysical Benefits in Austin, Texas</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microclimate regulation and mitigation of urban heat island effects</td>
<td>Unlikely to contribute to microclimate regulation or urban heat island effects</td>
<td></td>
</tr>
<tr>
<td>Carbon storage and sequestration</td>
<td>Unlikely to contribute to carbon storage and sequestration; however, water reuse is associated with reduced carbon emissions</td>
<td></td>
</tr>
<tr>
<td>Air pollutant removal</td>
<td>Unlikely to have air quality benefits; however, water reuse is associated with reduced emissions at power plants</td>
<td></td>
</tr>
<tr>
<td>Stormwater retention and runoff reduction</td>
<td>Some reduction in runoff volumes and peak flow with widespread implementation</td>
<td>Geosyntec 2016, Glick et al. 2016</td>
</tr>
<tr>
<td>Water filtration</td>
<td>Can lead to reduced total pollutant loads due to high runoff volume retention.</td>
<td></td>
</tr>
<tr>
<td>Biodiversity</td>
<td>With widespread implementation, they can reduce erosive events and peak flow, which can in turn lead to improved ecological health and aquatic life in urban streams.</td>
<td>Geosyntec 2016, Glick et al. 2016, Walsh et al. 2015</td>
</tr>
</tbody>
</table>

b. Economic Benefits

Cisterns provide economic benefits through stormwater capture and reuse. When stormwater is captured in cisterns, the risk of flooding and economic damage from flood events decreases. Since they serve to capture and hold water, less stormwater retention infrastructure may be required. However, for this latter benefit to be realized, the tanks must be reliably maintained and used (e.g., after a rainfall event they must be drained and ready to capture the next rainfall event). The other economic benefit cisterns provide is water supply, which can be used for non-potable applications, such as lawn watering, or in some cases can be coupled with treatment to supply a wider range of uses.
The economic benefits that cisterns generate related to reduced flood damage or avoided retention infrastructure costs depend on how widely cisterns are adopted and how much stormwater they are capable of capturing. These benefits materialize at a meaningful level when cistern use is widespread or targeted in areas where flooding is a problem.

Passive rainwater harvesting systems, such as rain barrels, provide limited opportunities for significant runoff reduction due to relatively small volumes and unpredictable operational readiness when a storm occurs (EPA 2013). This dramatically limits the economic benefits that cities can realize in the form of reduced retention infrastructure: primary stormwater capture infrastructure must still be built. Moreover, passive capture systems typically satisfy only a small fraction of the water demand of a typically homeowner, even for landscape irrigation.

Active cistern systems are larger volume systems (between 1,000 and 100,000 gallons) that capture and provide water supply. These are more appropriately scaled to multi-family dwelling units. They can range from simple, gravity-fed systems that provide untreated water for landscaping purposes to complex systems with treatment and pressure to supply a distribution system, for potable or gray-water use. The latter systems can supply a wider range of uses (EPA 2013). If the primary goal for cistern use is stormwater capture, the system must have a reliable source of demand, so that it can be drained prior to a storm. Some systems connect to backup stormwater management controls, such as a rain garden or the stormwater system itself, and empty stored water at low-flow periods to ensure adequate storage capacity for the next rainfall event. Automated monitoring systems are available to control the cistern capacity and time releases to weather events.

Optimal cistern sizing takes into consideration the local climate and water demand. A study of cisterns in Austin found that the maximum tank size to capture all available runoff in an average year in Austin would be 7,000 gallons. A tank this size would provide 46 percent of the typical water demand from a household in Austin (Kim 2011).

The economic benefits in water savings from these active systems would accrue slowly: the annual savings in water purchases of a system of this scale is in the low-hundreds of dollars per year. When a cheap, reliable source of water is available from the public water provider, cisterns do not compete economically. However, when water reliability becomes an issue, cisterns provide their owners with assurance that water will be available. This reliability factor has an economic value, which depends on
the cost of obtaining alternative supplies of water and the individual’s willingness to accept different levels of reliability from the public system.

Table 20. Range of Estimated Values of Economic Benefits of Porous Pavement in Austin, Texas

<table>
<thead>
<tr>
<th>Economic Benefit</th>
<th>Range of Values of Economic Benefits for Austin, Texas</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced Water Purchases</td>
<td>Reusing harvested rainwater onsite can offset water purchased from other sources.</td>
<td></td>
</tr>
<tr>
<td>Increased Water Reliability</td>
<td>During times of shortage, cisterns can reduce the timing and duration of water shortages by augmenting primary water supplies.</td>
<td></td>
</tr>
<tr>
<td>Avoided Stormwater Runoff Costs to City of Austin</td>
<td>$2 per cubic foot of stormwater diverted from system</td>
<td>American Forests 2002</td>
</tr>
<tr>
<td>Avoided Stormwater Runoff Fee Assessed to Property Owners</td>
<td>Site-specific, depending on percent reduction in impervious area.</td>
<td></td>
</tr>
<tr>
<td>Avoided Costs of Ecological and Species Habitat Management</td>
<td>Unquantifiable, but likely positive. Higher value for positive effects on habitat for sensitive species</td>
<td></td>
</tr>
</tbody>
</table>

b.i Beneficiaries

Cistern owners enjoy private benefits in the form of reduced water purchases and potentially increased water reliability if public water shortages occur. The public may enjoy benefits to the extent that cisterns reduce the peak flow of stormwater events, reducing the risk of flood damage for public and private property owners, and potentially reducing the investment required in stormwater retention infrastructure on public property.

c. Costs of Implementation

A small-scale rain barrel system that might be purchased from a hardware store and self-installed runs between $2 and $3 per gallon (City-Data 2010; EPA 2013). Active cistern systems are much more expensive. Large cisterns typically cost between $1.50 and $3.00 per gallon of storage. The rest of the system can vary significantly in cost, depending on the pumps, treatment systems, and distribution systems selected. The additional cost is typically between $2.00 and $5.00 per gallon but could be much more. The 7,000-gallon system specified by Kim (2011) for Austin costs between $7,500 and $12,000 (2016$). Operation and maintenance also varies depending on the system, ranging from virtually no maintenance at all for a simple rain barrel, to around $800 per year for routine maintenance and $350 per year for infrequent maintenance activities.
Table 21. Costs of Cisterns

<table>
<thead>
<tr>
<th>Cistern Construction Cost Per Cubic Foot of Water Quality Volume</th>
<th>Construction Costs/Cubic Foot$</th>
<th>Annual Maintenance Costs/Installation$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>$24.68</td>
<td>$350</td>
</tr>
<tr>
<td>High</td>
<td>$59.84</td>
<td>$</td>
</tr>
</tbody>
</table>

Sources: ¹City of Austin, ²Kim 2011 and City of Austin

A.2 Scoring Landscape Elements

This information provides a solid analytical foundation for the scoring of landscape elements based on their performance, which in turn facilitates developing a performance-based weighted rating for each element. With this approach, the City of Austin provides a landscape rating process based on science, transparency, and analytical rigor.

At this time, the ratings for the landscape elements are represented with symbols rather than numeric values; however, a GPA was calculated in way to summarize the overall benefit. Keep in mind that a numeric value is somewhat meaningless until target scores are identified for the parcels using Functional Green. The GPA is assuming that all ecosystem services are weighted the same although this is not likely to be true in Functional Green. We also recognize that the ratings will likely be adjusted at a later date after case studies are conducted, at which point numeric values will be more applicable.

Criteria for performance evaluation

The analysis included nine primary criteria to evaluate each landscape element that the Functional Green program will likely include. Six criteria are ecosystem services that the City of Austin identified as high priorities. An additional three criteria have significance to property development and use. The six ecosystem services are:

1. Microclimate regulation and mitigation of urban heat island effects
2. Carbon storage and sequestration
3. Air pollutant removal
4. Stormwater retention and runoff reduction
5. Water filtration
6. Biodiversity benefits
In addition to these ecosystem services, several additional criteria were included in the analysis to reflect property development and use considerations. Landscape elements in highly developed environments can improve human health and well-being. In addition, the economics literature describes the beneficial impacts that landscape elements can have on property values. To the extent that property markets perceive a landscape element as an amenity, increased demand and sale prices will reflect this. Lastly, landscape elements can also occupy space that would otherwise be developed. This can have implications for the financial returns to developers. Therefore, the three property development and use considerations in Functional Green are:

7. Human health and wellbeing
8. Effects on property values
9. Effects on developable area

Score Card

The landscape elements were scored against each other in terms of their expected relative performance for each of the nine criteria listed above. In the ratings, the consultants used a scoring system in which “A” means that the element is expected to perform well (in the top 20%) in comparison to the other elements evaluated. “B” means the performance of this element is in the mid-range when compared to the other elements evaluated (in the range of 50-70% performance). “C” means this element is on the low end of benefits when compared to the other elements evaluated (in the range of 20-40%), and “D” was assigned when minimal or no benefits were expected. In addition, a +/- was used as needed to differentiate between landscape elements in terms of their performance.
Table 22. Scores for landscape elements based on their relative performance with respect to nine criteria. See Appendix for more details about the scores.

<table>
<thead>
<tr>
<th></th>
<th>Microclimate regulation (degrees)</th>
<th>Carbon storage &amp; sequestration (kgC)</th>
<th>Air pollutant removal (g)</th>
<th>Stormwater retention (% of rainfall retained)</th>
<th>Water filtration (% load reduction)</th>
<th>Biodiversity benefits (habitat)</th>
<th>7. Property value ($)</th>
<th>Human well-being (public health)</th>
<th>Developable space (area)</th>
<th>GPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing tree</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3.7</td>
<td>2.3</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>3.56</td>
</tr>
<tr>
<td>Newly planted tree</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2.3</td>
<td>2</td>
<td>3</td>
<td>3.3</td>
<td>3.7</td>
<td>3</td>
<td>2.92</td>
</tr>
<tr>
<td>Green roof</td>
<td>3.3</td>
<td>3</td>
<td>2.7</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>3.7</td>
<td>3</td>
<td>4.3</td>
<td>3.44</td>
</tr>
<tr>
<td>Rain garden</td>
<td>2.3</td>
<td>2.3</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3.07</td>
</tr>
<tr>
<td>Vegetated wall</td>
<td>3.5</td>
<td>2.3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4.3</td>
<td>2.57</td>
<td></td>
</tr>
<tr>
<td>Planting beds</td>
<td>2.3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1.7</td>
<td>2.3</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2.26</td>
</tr>
<tr>
<td>Porous pavement</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>2.22</td>
</tr>
<tr>
<td>Cistern</td>
<td>1</td>
<td>1.7</td>
<td>1.7</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2.3</td>
<td>1.86</td>
</tr>
</tbody>
</table>

A = high performance, in 80-100% range  
B = mid-range performance, in 50-70% range  
C = low performance, in 20-40% range  
D = very low performance, in the bottom 1%

GPA:

\[
A++ = 4.3 \\
A+ = 4 \\
A = 3.7 \\
B+ = 3.3 \\
B = 3 \\
B- = 2.7 \\
C+ = 2.3 \\
C = 2 \\
C- = 1.7 \\
D = 1
\]

When comparing all of the ecosystem services equally we notice that existing trees are highly beneficial across the board. Green roofs are surprisingly also very beneficial and, in some ways, provide more benefit than existing trees. This addresses the debate on whether natural landscape elements are always more beneficial than constructed green infrastructure elements. As we can see comparing existing trees and green roofs, they are all relatively close in scoring all ecosystem services. The biggest
difference in score is between their developable space benefit, which is existing tree's lowest score. As discussed before this is due to green roofs being very flexible in the kind of development it can be installed for.

Another important take away from the score card is to prioritize particular ecosystem services. When comparing the GPAs of cisterns and plant beds, plant beds have an overall higher score. However, plant beds did not provide any kind of high performance and only achieved mid-range performance in human wellbeing and developable space. Cisterns on the other hand are highly proven to be beneficial in stormwater retention, since that is what they are constructed for doing. When a private land developer compares these two landscape elements it is important to acknowledge what ecosystem services are most important. Some landscape elements are more localized in the kinds of benefits they can provide than others.

B. Cost Benefit Calculator

The results from comparing the model buildings to each other are shown below.

Table 23: Comparison Ecosystem Services, Cost and Benefit for 5 Austin Buildings

<table>
<thead>
<tr>
<th>Ecosystem Services</th>
<th>Arnold</th>
<th>5 Congress</th>
<th>7th &amp; Rio</th>
<th>Austonian</th>
<th>Galileo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Storage (kg C)</td>
<td>486,801</td>
<td>1,165,260</td>
<td>79,420</td>
<td>204,660</td>
<td>37,603</td>
</tr>
<tr>
<td>Carbon Sequestration (kg C/year)</td>
<td>543</td>
<td>5,576</td>
<td>-</td>
<td>596</td>
<td>-</td>
</tr>
<tr>
<td>Air Pollutant Removal (g/year)</td>
<td>11,154</td>
<td>20,280</td>
<td>3,732</td>
<td>5,151</td>
<td>11,123</td>
</tr>
<tr>
<td>Stormwater Retention (gal)</td>
<td>612,096</td>
<td>117,984</td>
<td>16,331</td>
<td>136,285</td>
<td>11,209</td>
</tr>
</tbody>
</table>

Total vegetated surface area (in acres) | 1.11 | 0.20 | 0.08 | 0.15 | 0.63 |
Percent green surface area for site | 25.46% | 21.54% | 12.89% | 22.38% | 9.54% |

DOLLAR VALUE OF ECO SYSTEM SERVICES (ANNUAL) |
| Arnold | $1,245,637 |
| 5 Congress | $1,130,144 |
| 7th & Rio | $239,418 |
| Austonian | $285,192 |
| Galileo | $389,259 |

TOTAL COSTS |
| $2,106,336 |

First, the table above indicates the low and high ecosystem service effects each of the buildings provide from the landscape elements they have implemented. As we saw before, the Arnold is our biggest building and has the highest diversity of green infrastructure. Across the board the Arnold is creating the highest benefit of ecosystem services for carbon storage and sequestration and stormwater retention. However, despite the size difference, the Austonian has a high effect of contributing up to 89,406 grams of air pollution removal a year. This is higher than the Arnold’s high estimate of 20,280 grams removed per year. The difference between the landscape elements between the two buildings, that contribute to air pollution removal, is the Austonian’s green roof. The Austonian has not only a
green roof, but an intensive and extensive roof. This variety provides all of the benefits that green roofs provide, including air pollution removal, which green roofs scored a B+ in.

When considering the total costs, we see that the Arnold was estimated to have paid over $18 million at the high estimate for their extensive and diverse landscape elements. This investment was beneficial in providing ecosystem services, however does not contribute much to the return as compared to the other buildings. The Austonian is achieving the highest dollar value of benefit per acre, primarily from the high benefits from implementing so much green roof. Green roof is able to provide so much dollar value due to our calculations of price at $8 to $25 a square foot. As stated before, keep in mind there is not much evidence and literature providing the definite dollar benefit compared to the cost. Green roofs are clearly very beneficial in most of the ecosystem services and achieved the highest GPA, but this doesn’t make it the best landscape element for every building. Buildings have different capabilities and depending on location, exposure, and use, can get different results.

C. Benefit Locations

Austin Urban Street Tree Planting
Figure 1: Priority Tree Planting Census Tracks of Austin, Texas

The map above is the results of the City of Austin’s Tree Planting Prioritization tool. Based on the factors of the layers they used (public health & safety, air quality, environmental justice, water quality, critical places, forest replenishment, forest preservation & development impacts, and urban heat island) the areas in red are the census tracks that are most attractive for planting trees. Being the most attractive for planting trees means they are the census tracks with the poorest public health and safety, the worst air quality, the most environmental justice issues, poorest water quality, the most critical places, the least forest replenishment, the least forest preservation and development impacts and the most vulnerable to urban heat island effect. The top five areas in red that achieved the highest priority score include East Cesar Chavez, Holly, Govalle, Windsor Hills, Heritage Hills, North Lamar, and
Johnston Terrace MLK, MLK-183, Govalle (Halter 2015). These are primarily areas surrounding I-35 highway.

This information can be used to better understand vulnerability in Austin. This analysis used a lot of important data layers that would be beneficial for recreating in order to attain the ecosystem services of our own study. These areas of very high priority for planting trees are very likely to be high priority for implementing green infrastructure and Functional Green.

*Functional Green Zip Code GIS Tool*

*Figure 2: Map of high developed area considered in Functional Green over Austin zip codes.*
Table 24: Attribute table of selected zip code 78701 including the ecosystem services of under all building plans.

The map above shows the highest developed area of Austin that will be used for implementing Functional Green. The table shows the results of the GIS tool’s output when the zip code 78701 is selected. If zip code 78701 was transformed with the same landscape elements as any of the buildings these are the prospective benefits. Looking the table since we picked 78701 our first row shows us that if all of the zip code was covered in the landscape elements that the Arnold has, we would have 9,184,423 kg of C stored, 43,208 kg of C sequestered a year and so on down the columns. Biodiversity is represented with 0s in this tool because square feet of habitat has not yet been quantified as a level of biodiversity benefit for this project yet.

It is noticeable here as well that the Austonian’s landscape elements provides the most benefit in they were spread across an entire zip code. As we saw before in the calculator and the score card, green roofs have been very beneficial in many ecosystem services. One could also see that the zip code with the highest development, 78753 with over 2,945,147 square feet of high development, could store up to 47,450,885 kg of Carbon and could be worth a monetary value of $39,877,297 total in ecosystem services.

This tool isn’t expected to be used to anticipate actually covering an entire zip code with green infrastructure, but to compare the landscape element plans and see how benefits can be maximized in particular zip codes. The tool will allow a city planner to compare zip codes and how they will benefit, depending on how developed they are.

Survey Data GIS Maps:
Lastly, the results of the Austin citywide survey data results didn't indicate an obvious pattern other than a slight concentration of “Very Dissatisfied” respondents in a few areas along Interstate 35. This could be useful information if stormwater retention is actually very poor in most areas within 2 miles of the highest developed area. Since we can't see many condensed areas of issues we might assume that stormwater retention needs improvement in all of these places.
VI. Conclusion

Based on this research we can conclude that green infrastructure will produce biophysical and economic ecosystem service benefits for Austin. We created the score card that will allow Austin to set biotope area factor standards and allow land developers to identify what kind of landscape elements they can use to meet the ratio. Any limitations of this score card are due to the lack of literature identifying the other ecosystem services for some of the landscape benefits that are very focused on one service. For example, we know a lot about how trees are beneficial and how to quantify those benefits because we have helpful tools like iTree that were created for doing so. However, other landscape elements, like the cistern, are proven to be beneficial in stormwater retention because that is what they are built for, but little information is studied on the other kinds of benefits they provide in terms of services like biodiversity.

The cost benefit calculator was successful in creating a tool that multiplied the area of landscape elements to understand the ecosystem services, costs and economic benefits. We identified here that the green roof can be a very cost-effective landscape element in providing high benefit for all of the ecosystem services studied. This tool could be made better by quantifying the services of biodiversity and human wellbeing further to a understandable benefit like square feet of pollinator species habitat, or happiness level increase in humans. Those ecosystem services were left out of most equations in the calculator and including them would allow us to better compare benefits. A better representation of the costs would make this tool better for obtaining the true cost of implementation by considering installment, maintenance, replacement, pruning, and the price paid by the residents in the buildings to live in a place with these elements.

Lastly, we identified priority areas of Austin that will most likely benefit from these ecosystem services. To improve the Austin Tree Planting Prioritization tool would include substituting some of the layers they used, for our ecosystem services to better understand the vulnerable populations in need for our particular services provided by green infrastructure. From the Functional Green Zip Code tool we can now see what zip codes are going to achieve the most benefit from the ecosystem services; however this tool can be improved by actually indicating the building square footages and adding the minimum Biotope Area Factors to get a more accurate representation of the benefit in this area. Finally, with the City Survey Mapping, we have an effective method in identifying concern and where it is concentrated.
in order to identify areas to prioritize. If this survey asked more questions related to our ecosystem services we could identify further geographic trends and improve the conditions in these areas with our ecosystem services from Functional Green.

VII. Recommendation

Based on this study, we now understand that the cheapest landscape elements do not necessarily provide the most benefit. The City of Austin should understand that land developers are likely to implement the cheapest landscape elements, regardless of how beneficial they are, in order to meet their biotope area factor. The city should provide some sort of incentive for implementing large green roofs and keeping their existing trees in order to make developers provide more benefit for the city.

Finally, when evaluating ecosystem services, it is crucial to identify the public priority and how the citizens of Austin feel about green infrastructure. I recommend that the city conduct a city-wide social survey to obtain the public’s need. From this survey we should find out other ecosystem services and landscape elements that we didn’t consider before in order the get the most benefit as possible.

VIII. Acknowledgements


IX. Works Cited


Austin 2014, City of. “Existing Credits for Green Roof Projects in Austin.”


Austin, City of. 2017. “Existing Credits for Green Roof Projects in Austin.”


Date, Breuning J. No. “The Economics of Green Roofs from the Perspective of the Commercial Client: A Cost Benefit Analysis of Extensive Green Roofs.” *Green Roof Service, LLC.*


X. Appendix

Appendix A. Austin Tree Planting Prioritization
<table>
<thead>
<tr>
<th>Category</th>
<th>Planting Factor</th>
<th>Data Set Used in Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public Health &amp; Safety</td>
<td>• Age dependency ratio (Dependent population / working-age population)</td>
<td>U.S. Census 2010</td>
</tr>
<tr>
<td></td>
<td>• Obesity risk</td>
<td>Travis County Communities Putting Prevention to Work</td>
</tr>
<tr>
<td></td>
<td>• Average mortality rate: diabetes</td>
<td>BRFSS Survey</td>
</tr>
<tr>
<td></td>
<td>• Average mortality rate: heart disease</td>
<td>Texas DSIS Center for Health Statistics Death Data</td>
</tr>
<tr>
<td></td>
<td>• Average mortality rate: chronic lower respiratory disease</td>
<td>Texas DSIS Center for Health Statistics Death Data</td>
</tr>
<tr>
<td></td>
<td>• Crime</td>
<td>Crime Incidents 2009-2011</td>
</tr>
<tr>
<td>Air Quality</td>
<td>• Average CO emissions</td>
<td>CAMPO Road Emission Projections 2035</td>
</tr>
<tr>
<td></td>
<td>• Average CO2 emissions</td>
<td>CAMPO Road Emission Projections 2035</td>
</tr>
<tr>
<td></td>
<td>• Average NOx emissions</td>
<td>CAMPO Road Emission Projections 2035</td>
</tr>
<tr>
<td></td>
<td>• Average VOC emissions</td>
<td>CAMPO Road Emission Projections 2035</td>
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<tr>
<td>Environmental Justice</td>
<td>• Environmental Justice Areas (Low Income &amp; Minority)</td>
<td>Environmental Justice Traffic Analysis Zones</td>
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<td>• Toxic Release Inventory</td>
<td>EPA Toxic Release Inventory</td>
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<tr>
<td>Water Quality</td>
<td>• % Impervious Surface</td>
<td>Building Footprints 2006; Transportation Features 2006</td>
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<tr>
<td></td>
<td>• Average water quality score</td>
<td>Watershed Integrity Scores</td>
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<td></td>
<td>• % creek buffers</td>
<td>Creek Buffers</td>
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<td></td>
<td>• % floodplains</td>
<td>Austin Fully Developed Floodplain</td>
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<td>Critical Places</td>
<td>• Schools</td>
<td>Schools</td>
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<td></td>
<td>• Hospitals</td>
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<td>• Libraries</td>
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<td></td>
<td>• Rec centers</td>
<td>Recreation Centers</td>
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<td>• Health center</td>
<td>Health Centers</td>
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<td></td>
<td>• Nursing home</td>
<td>Nursing Homes</td>
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<td></td>
<td>• Population density (people per square mile)</td>
<td>U.S. Census 2010</td>
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<tr>
<td>Forest Replenishment</td>
<td>• # trees distributed by PARD</td>
<td>PARD Forestry Annual Planting Numbers</td>
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<td></td>
<td>• # trees distributed by NeighborWoods/TreeFolks</td>
<td>NeighborWoods Tree Delivery Numbers</td>
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<td></td>
<td>• Possible planting space</td>
<td>Possible Planting Space</td>
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<tr>
<td>Tree Preservation &amp; Development Impacts</td>
<td>• Tree removals</td>
<td>Tree Removal Permit Points</td>
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<td>• Building permits</td>
<td>Growth Watch</td>
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<td></td>
<td>• Environmental sensitivity</td>
<td>Vacant Land Inventory</td>
</tr>
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<td></td>
<td>• Imagine Austin growth centers</td>
<td>Imagine Austin Centers</td>
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<tr>
<td>Urban Heat Island</td>
<td>• Average Surface temperature</td>
<td>Landsat 7 satellite imagery</td>
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Table A.1: Austin Tree Planting Prioritization layer categories and the planting factors and data sets used in the city analysis.