STACKING GREEN INFRASTRUCTURE BENEFITS:
A Spatial Multi-Criteria Approach to Green Infrastructure Planning in Seattle, Washington

A thesis submitted by

Kai Ying Lau

in partial fulfillment of requirements for the degree of

Master of Science

in

Urban and Environmental Policy and Planning

Tufts University

August 2018

Advisor: Barbara Parmenter, PhD

Reader: Sumeeta Srinivasan, PhD

ABSTRACT

Green infrastructure, defined as any greenery within urban areas, provide a myriad of benefits and services to improve the quality of life for residents. This multi-functionality makes it popular as a sustainable development tool. However, green infrastructure is mainly used or defined as low-impact development technology to mitigate stormwater runoff. Research indicates that there is a lack of inclusion of multiple green infrastructure benefits in decision-making, and a gap in the analysis of overlapping spatial needs for green infrastructure benefits. This thesis focuses on creating a spatial multi-criteria decision-analysis (S-MCDA) model to determine where green infrastructure will provide multiple ecosystem services. This model determined areas of multi-benefit priority areas for green infrastructure in the City of Seattle. Specifically, this thesis analyzed the spatial, land use and ownership properties of the following ecosystem services: stormwater runoff mitigation, air pollution mitigation, carbon sequestration, urban heat island mitigation, habitat resilience, and access to green space. Social vulnerability was also included in the analysis to investigate any existing social and environmental inequities. Through the S-MCDA analysis the results of this study indicate that the districts with the highest priority need for multiple green infrastructure benefits are: the Southeast, North Seattle, and the industrial and manufacturing areas. Spatial statistics analysis results show there is opportunity and demand for siting green infrastructure based on the need for multiple benefits.

TABLE OF CONTENTS

Tables and Figures

Chapter 1 // Introduction

Green infrastructure within urban areas, such as urban forests, provide a myriad of benefits and services to improve the quality of life for urban residents (Forest Ecosystem Values Report, Kabisch 2015). According to the Presidents Council for Sustainable Development (PCSD), green infrastructure can be used to “guide more efficient and sustainable land use and development patterns as well as protect ecosystems” (PCSD 1999 P64, from Lennon 2015). Hence, these benefits, or ecosystem services, can also provide sustainability solutions as pressure increases on municipalities to plan for resilience amidst changes that affect economic, environmental, and social justice goals (Ahern 2011 from Meerow and Newell 2017; Lennon and Scott 2014 from Meerow and Newell 2017, Kabisch 2015).

Planners and policy-makers look to green infrastructure as a possible framework to achieve sustainable development because of its multifunctionality. By providing a range of benefits, green infrastructure can improve economic, environmental, and social aspects of people’s lives. However, green infrastructure can take on different definitions depending on which state, city, or organization is defining it. Some define it as any type of green space ranging from larger green spaces such as wetlands and public parks for recreation, to rain gardens and bioswales whose main purpose is stormwater runoff mitigation. Despite inconsistency in defining green infrastructure, it is highly promoted among researchers, municipalities, and organizations. Some examples of cities that have policies strongly supporting the implementation of green infrastructure include Detroit, New York City, and London (Meerow and Newell 2017).

Though researchers highlight the environmental, economic, and social benefits of integrating green infrastructure into urban planning (Kabisch 2015), there is a gap in examining how the spatial need for ecosystem services affects green infrastructure planning (Kabisch 2015). Additionally, there is a lack of inclusion of multiple green infrastructure benefits in project development and the general decision-making process (De Groot et al 2010 from Kabisch 2015; Kremer et al 2016, Newell et al 2013 from Meerow and Newell 2017).

This thesis will look at how the inclusion of multiple ecosystem services might influence siting of green infrastructure in Seattle, Washington. To address the lack of planning models that explore ecosystem service tradeoffs and synergies (Hansen & Pauleit, 2014, from Meerow and Newell 2017), this thesis will explore the change in priority areas for green infrastructure based on different weighted benefits. This thesis proposes a GIS model showing areas in Seattle that have a high need for multiple green infrastructure benefits. A literature review of existing multi-criteria GIS models focused on green infrastructure multi-functionality helped to develop a methodology and identify which ecosystem services to include in the model. This thesis builds on this literature review to create a similar multi-criteria GIS model applied to the City of Seattle, a city where several plans address green infrastructure services. Results from this multi-criteria GIS model aim to:

- Highlight high priority areas for siting green infrastructure where there is a high need for multiple environmental or social benefits.
- Determine where synergies and tradeoffs are for green infrastructure ecosystem services.

Research Questions

Based on the goals of this thesis, the research questions for this analysis are:

- What existing spatial multicriteria GIS models explore the need for green infrastructure and its associated ecosystem services?
- Where in Seattle has the highest need and demand for several ecosystem services provided by green infrastructure?
- Is there a spatial relationship between various ecosystem services? What are the trade-offs and synergies planners need to consider when siting green infrastructure?

Chapter Summaries

Before delving into the analysis, Chapter 2 includes definitions of green infrastructure and ecosystem services. Chapter 3 provides a background of Seattle and expands on how ecosystem services are relevant to current policy and planning. Chapter 4 includes a brief overview of spatial multi-criteria decision analysis (S-MCDA) models, a methodological review of 9 S-MCDA models, and summary of how ecosystem services are measured. Having established a basic workflow for what to include in this GIS analysis, Chapter 5 provides a more detailed description of the methodology used for this analysis. The last two chapters of this thesis are the results and discussion (Chapter 6), and recommendations and conclusion (Chapter 7).

Chapter 2 //

Green Infrastructure and Ecosystem Services

Overview

This chapter explores the various definitions given for green infrastructure. In this report, green infrastructure will be defined as: the green network in a city, such as parks, street trees and rain gardens, that provides a diversity of social and environmental ecosystem services for a more resilient city.

A brief introduction to what ecosystem services will be addressed in this thesis is provided. These ecosystem services include: stormwater runoff mitigation, air pollution mitigation, carbon sequestration, urban heat island mitigation, habitat connectivity and buffers, and access to green spaces. Social vulnerability will also be discussed in relation to access to green space. Environmental and social issues for each ecosystem service are mentioned along with how they can be mitigated with the implementation of green infrastructure.

What is Green Infrastructure?

The concept of green infrastructure shifts in definition depending on who is defining it and for what purpose. Green infrastructure definitions can be split into two groups: 1) a green network consisting of different types of greenery, and 2) green stormwater infrastructure or low-impact development (LID). Both definitions acknowledge that green infrastructure is multifunctional, meaning it can provide for a variety of social and ecological benefits even it if is installed for one specific purpose. For example, green infrastructure or LID is often sited based on stormwater runoff mitigation needs, but it is often promoted as a best management practice that also brings other benefits such as beautifying streets and neighborhoods (Kremer, Hamstead, and McPhearson 2016; Meerow and Newell 2017)

Green Infrastructure as a Green Network

Green infrastructure as a concept originated from ecological planning (Droguett 2011). Green infrastructure supports the larger ecosystem network in an urban place, but to build a resilient network complex interactions between green infrastructure and urban ecosystems need to be understood (Droguett 2011). Different types of green infrastructure include urban green spaces, such as greenways, parks, rain gardens, street trees, and bioswales. These green spaces provide multiple social and ecological benefits, such as stormwater runoff mitigation and carbon sequestration (Lo, Byrne, and Jim 2017). Though green spaces can individually provide such benefits, it is the interconnectedness of green spaces which enhance the benefits as well as conserves existing natural ecosystems (Meerow and Newell 2017). Ecosystem benefits, also known as ecosystem services will be discussed in more detail in the next section.

Green Infrastructure as Low-Impact Development Technology

The EPA defines green infrastructure as “an adaptable term used to describe an array of products, technologies, and practices that use natural systems or engineered systems that mimic natural processes to enhance overall environmental quality and provide utility services” (USEPA n.d.). In other words, green infrastructure technology that provides stormwater management makes use of the process of natural ecosystems, such as infiltration, to improve environmental issues. Additionally, the Clean Water Act 2009 (HR4202) defines green infrastructure as “a stormwater technique that preserves, restores, enhances, or mimics natural hydrology” (Congress 2009). The popularity of using green infrastructure for stormwater management is because it is an alternative to building large and expensive gray infrastructure, while also providing additional benefits (Meerow and Newell 2017).

Cities that have defined green infrastructure specifically for stormwater management include New York City, Chicago, and Philadelphia (Droguett 2011). New York City has a Green Infrastructure Program whose goal is to prevent stormwater from entering the sewer systems using green infrastructure, effectively helping to reduce combined sewer overflows (CSOs) (NYCEP, n.d.). They define green infrastructure as a practice that "promotes the natural movement of water collecting and management stormwater runoff" from impervious surfaces and directs runoff "to engineered systems that typically feature soils, stones and vegetation" (NYCEP, n.d.). NYC's green infrastructure program also briefly mentioned the additional benefits of aesthetics and air pollution mitigation.

Similarly, the City of Chicago has a Green Stormwater Infrastructure Strategy where they use the term "green stormwater infrastructure" to encompass "strategies for handling storm precipitation where it falls rather than after it has run off into a sewer system" (Chicago 2014). However, one of the strategies in Chicago's Climate Action Plan identifies using green infrastructure to mitigate urban heat areas (USEPA n.d.; City of Chicago n.d.) Another example is Philadelphia's Green City, Clean Water program, which aims to meet goals in the City's Clean Water Act by installing green stormwater infrastructure (Philadelphia Water Department n.d.). Philadelphia's Water Department specifies green stormwater infrastructure as systems that "intercept stormwater, infiltrate a portion of it into the ground, evaporate a portion of it into the air, and in some cases release a portion of it slowly back into the sewer system" (Philadelphia Water Department n.d.). The Green City, Clean Waters program is also recognized as a strategy to mitigate climate change through carbon sequestration, air pollution mitigation, and reduce the urban heat island effect (Philadelphia Water Department n.d.).

Green infrastructure projects in cities have mainly been sited based on stormwater management needs despite the acknowledgment of its multifunctionality and benefits that can help to combat climate change (Ahern 2013). If cities wish to increase their resiliency through flexibility and diversity of green infrastructure they need to go beyond a focus on siting for stormwater management and expand to siting based on its ability to address multiple social and environmental needs (Kabisch et al. 2016; Madureira and Andresen 2014; Meerow and Newell 2017). Green infrastructure offers cities an opportunity for innovative and interdepartmental planning to develop more holistic strategies that address complex interactions between multiple social and environmental issues (Hansen and Pauleit 2014).

Currently, green infrastructure benefits are thought of as positive externalities with a focus on stormwater management. These additional benefits need to be treated as goals by cities and be a primary consideration when siting green infrastructure.

This report focuses on prioritizing all ecosystem benefits when siting green infrastructure. Green infrastructure in this report is defined as: the green network in a city, such as parks, street trees and rain gardens, that provides a diversity of social and environmental ecosystem services for a more resilient city.

Green Infrastructure Ecosystem Services

Overview

Defining green infrastructure on a broader scale to include all types of greenery acknowledges that green infrastructure enhances the overall function of natural and social ecosystem through several channels, or ecosystem services (Droguett 2011). The development of green infrastructure with a focus on addressing multiple ecosystem services allows urban areas to: 1) understand the complexity and interaction of urban ecosystems, 2) increase their ecological and social functioning, and 3) maximize human benefits (Pickett and Cadenasso 2007). Ecosystem services are defined as benefits provided to and consumed by humans resulting from natural ecosystem processes (Dobbs, Escobedo, and Zipperer 2011).

Green infrastructure ecosystem services included in this thesis are divided into two groups: 1) environmental ecosystem services and 2) cultural ecosystem services. Environmental ecosystem services include stormwater runoff mitigation, air pollution mitigation, carbon sequestration, urban heat island mitigation, and habitat resiliency. Cultural ecosystem services include health and wellness where access to green space and social vulnerability will be discussed. Below is a summary of how each ecosystem service addresses environmental or social issues.

Environmental Ecosystem Services

Stormwater Runoff Mitigation

Stormwater runoff leads to untreated contaminated water reaching surrounding water ecosystems due to the inability of sewer systems to handle water volume above a certain threshold. Green infrastructure aids in mitigating stormwater runoff by decreasing flow velocity to encourage infiltration (Droguett 2011; Hatt, Fletcher, and Deletic 2009).

Air Pollution Mitigation

Exposure to outdoor air pollution is higher in urban areas (Larondelle and Lauf 2016), increasing the risk of heart disease, lung cancer, and respiratory diseases (World Health Organization 2018b). Mitigating air pollution with greenery through the removal of pollutants reduces human exposure to harmful particles, which is expected to improve public health.

Carbon Sequestration

Carbon dioxide is one of the main greenhouse gases that negatively impacts climate change, but it is readily sequestered from the atmosphere and used by plants for growth (Baur et al. 2015). Carbon sequestration is an important ecosystem service provided by green infrastructure not just to remove carbon from the atmosphere, but also by reducing energy costs with increased tree canopy cover (McPherson et al. 1997).

Urban Heat Island Effect Mitigation

Urbanization has led to an increase of impervious surfaces that absorb heat, and a reduction in vegetation that would provide cooling through transpiration (Weng 2001). The resulting urban heat island (UHI) effect can lead to additional heat stress on urban residents (Scherer et al. 2013). The presence of urban trees can mitigate the UHI effect through transpiration (McPhearson, Kremer, and Hamstead 2013).

Habitat Resiliency

Urbanization has not only caused the urban heat island effect, but also fragmented and endangered the biodiversity of natural wildlife habitats in an urban landscape (Ahern 2011). To combat the negative consequences of habitat fragmentation and the edge effect in urban areas, green infrastructure connections or buffers is a way to provide additional space for animals to traverse and protect biodiversity (Bolger et al. 2000).

Cultural Ecosystem Services

Access to Green Spaces and Social Vulnerability

Access to green spaces has been shown to positively influence physical and mental health and wellness (Meerow and Newell 2017; Kremer, Hamstead, and McPhearson 2016; McPhearson, Kremer, and Hamstead 2013; Madureira and Andresen 2014). Unfortunately, access to green space is disproportionate due to several factors such as income, race, and age. Therefore, including social vulnerability into any green infrastructure analysis is important because it investigates any existing inequities in access to green space.

SUMMARY

This thesis defines green infrastructure as any type of greenery in an urban area that is part of the larger green network. Green infrastructure is known to provide multiple ecosystem benefits, several of which have been introduced here and will be included in the final analysis. The next chapter dives deeper into the need and demand for each ecosystem service, and the relevance of providing these ecosystem services to Seattle, Washington.

CHAPTER 3 //

CASE STUDY OF SEATTLE, WASHINGTON

OVERVIEW

Before performing the analysis, this chapter builds understanding of how green infrastructure ecosystem services are relevant to Seattle. This chapter provides a background of Seattle and the relevance of ecosystem services to planning in Seattle.

BACKGROUND

Geography

Located 100 miles south of the US-Canada Border, Seattle is about 83 square miles and is surrounded by water on the East (Lake Washington) and the West (Puget Sound) (100 Resilient Cities 2016; Seattle Public Utilities 2009). Bodies of water that cut across Seattle include the Duwamish River, and several bays that allow passage between Lake Washington and Puget Sound (Seattle Public Utilities 2009).

City Profile

Seattle is known for its rapidly growing economy and quality of life (100 Resilient Cities 2016). It is the largest city in Washington State with a population of around 690,000 people in 2016 (100 Resilient Cities 2016). From 2014 to 2015, Seattle was ranked 4th among the largest US cities for growth and experienced a population growth of 2.3% (100 Resilient Cities 2016). By 2024, it is projected that there will be an increase of 48,000 households and 84,000 jobs (100 Resilient Cities 2016). According to the 2010 Census, Seattle's population was mainly White (69%) with Asians (14%) and Black or African American (8%) as the two largest minority groups (Census Bureau 2010).

The land use in Seattle can be split into 6 main categories (Figure 1). About 85% of the land in Seattle is composed of either residential land (63%), institutional and public buildings (13%) or commercial land (10%). The remaining 15% of land is split between industrial (6%), open space and recreation (3%), and transportation (2%).

There are 7 council districts within Seattle and 91 neighborhoods (Figure 2). In addition to these political boundaries, the City of Seattle has also established urban centers and villages as part of its Comprehensive Plan (Figure 3). Urban centers and is part of Seattle's strategy to focus future growth in specific areas (Office of Planning & Community Development 2015). These centers and villages are dense and mixed-use developments that support housing and employment growth, walkability and transit-oriented development, and access to green spaces (Office of Planning & Community Development 2015). There are four types of urban villages:

1. Urban Centers: These neighborhoods are the densest and serve as regional centers. Urban centers are mixed-use, and provide diverse housing and employment.
2. Manufacturing/Industrial Centers: These centers are where Seattle's industrial businesses are concentrated.
3. Hub Urban Villages: Like urban centers, these neighborhoods provide housing and employment; however, they are not as densely developed.
4. Residential Urban Villages: These villages serve mainly residents and surrounding communities.

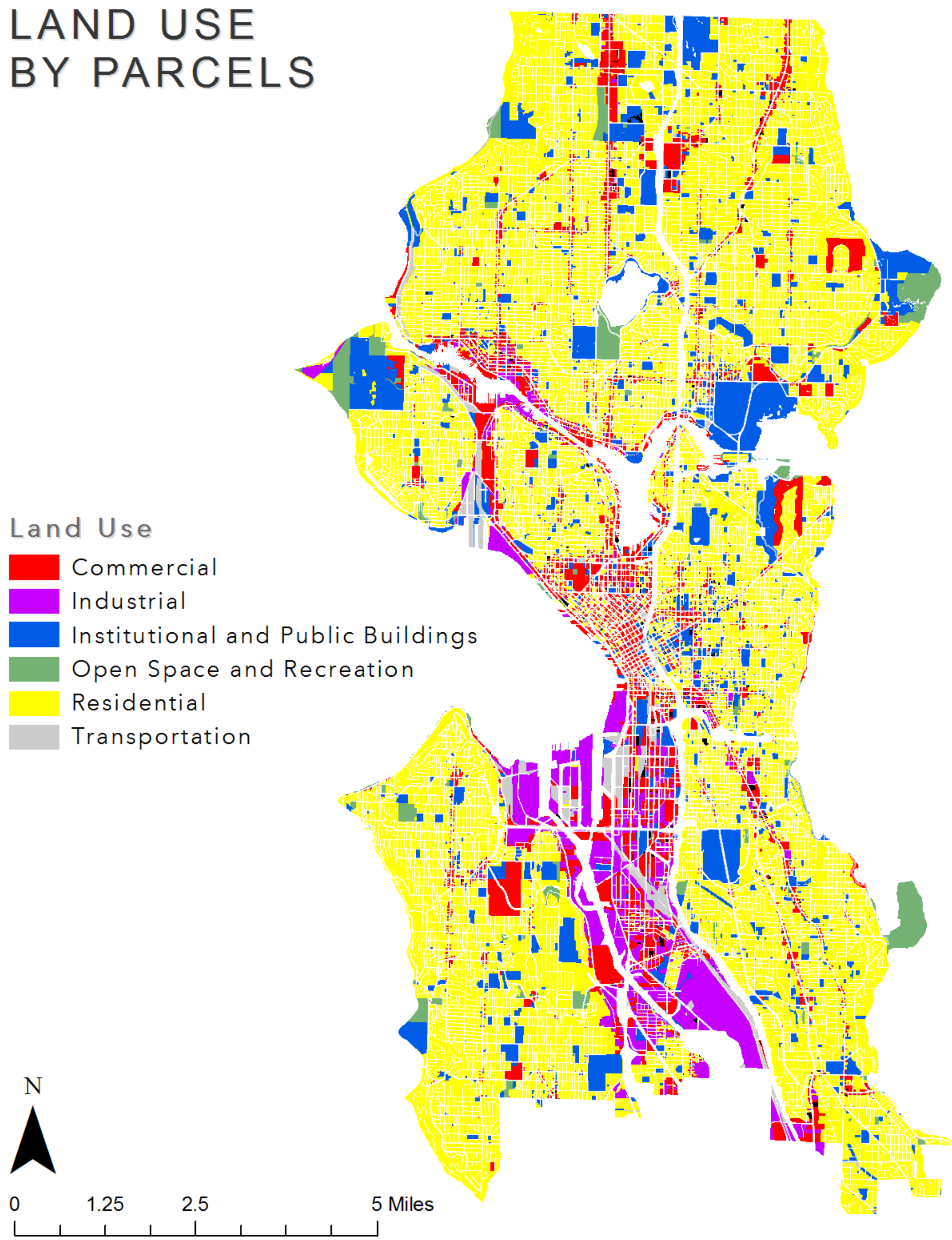

Figure 1: Land use map of Seattle. *Data source: King County GIS Open Data*

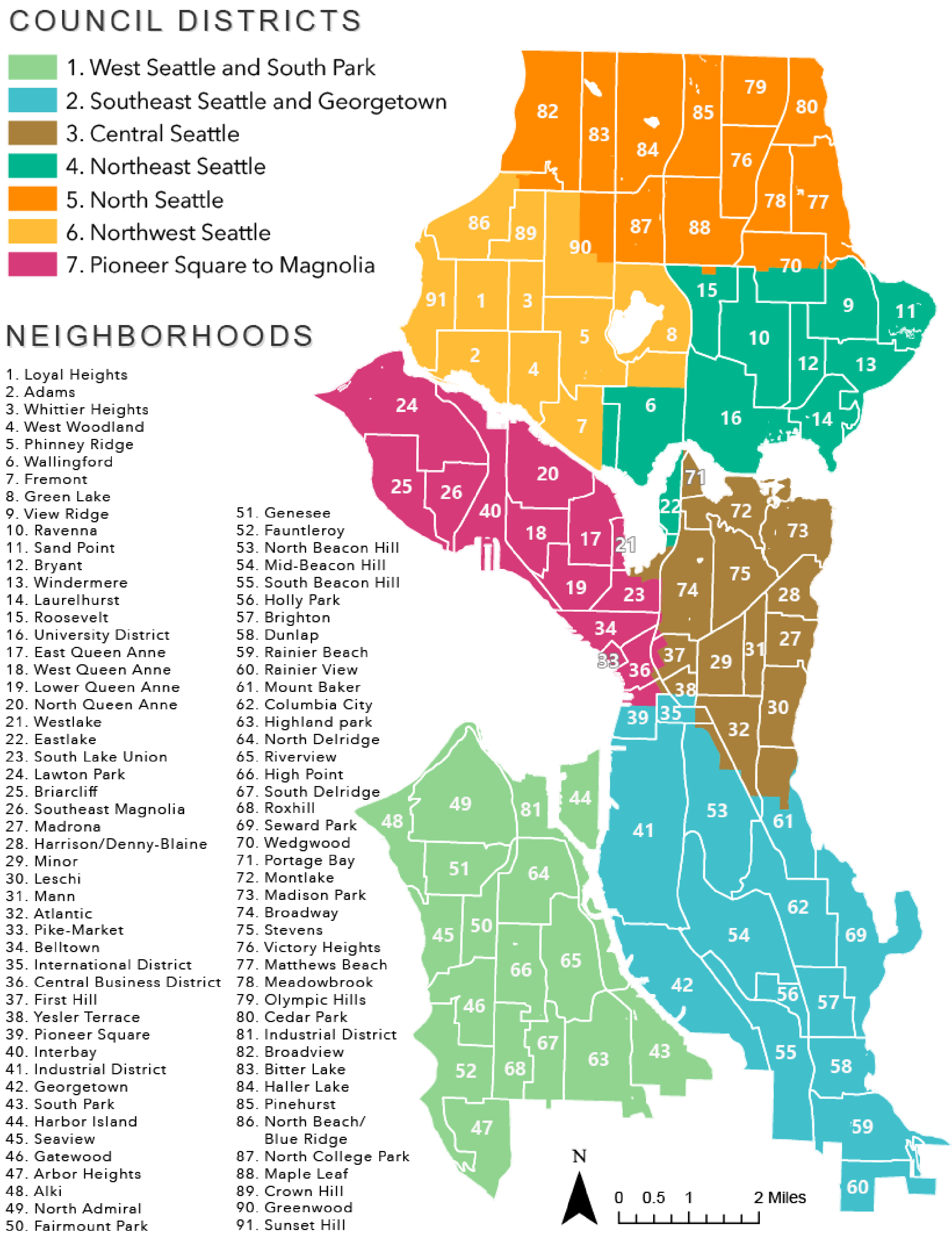

Figure 2: Council district and neighborhood map of Seattle. *Data source: City of Seattle*

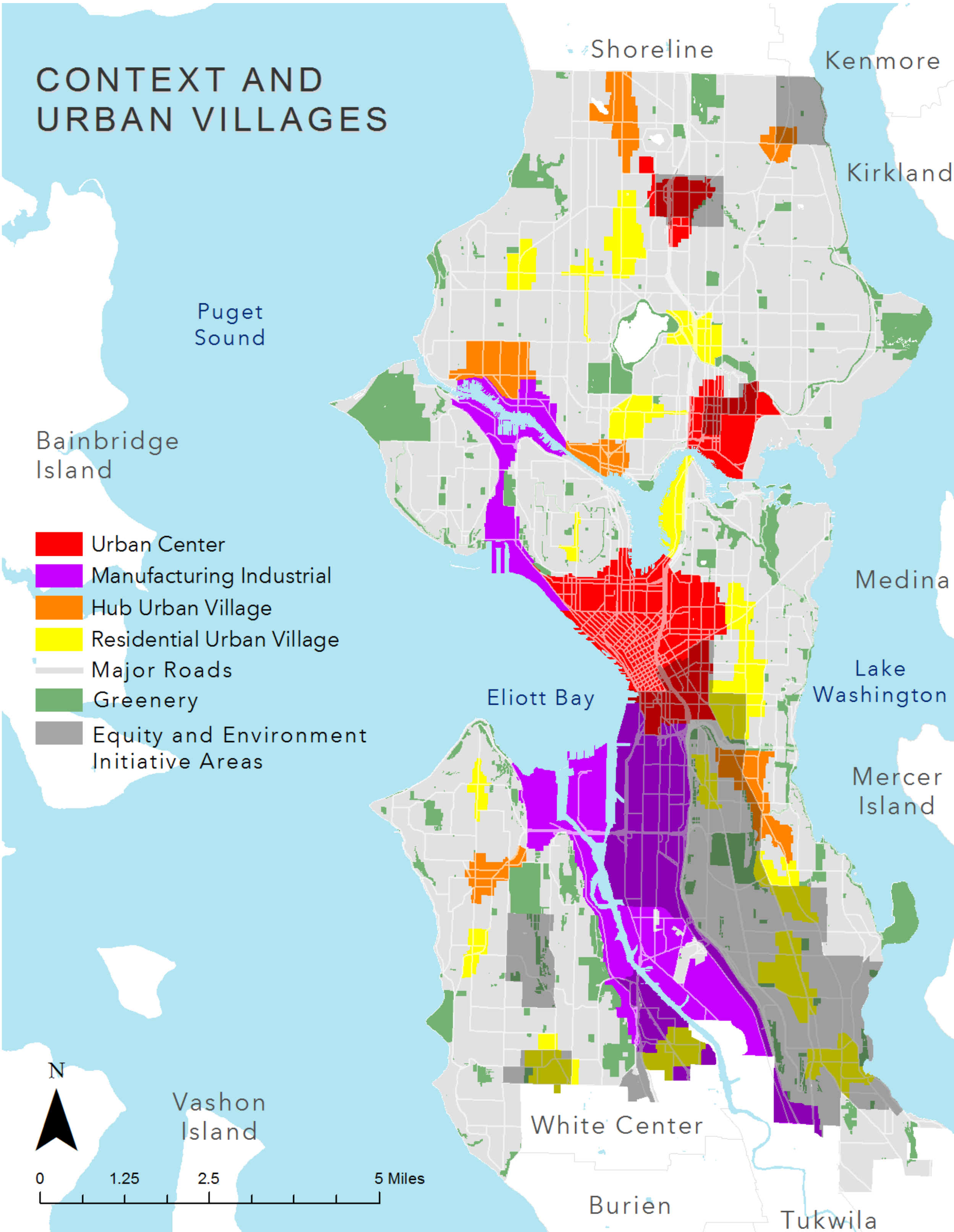

Figure 3: Context and urban village map of Seattle. *Data source: City of Seattle*

Resilience

Although Seattle is surrounded by beautiful water bodies and the Olympic Mountains further east beyond Lake Washington, climate change threatens to impact the City's dependence on the available natural resources (100 Resilient Cities 2016). To prepare for this, Seattle joined the 100 Resilient Cities (100RC) network in 2016 (100 Resilient Cities 2016). 100RC focuses on building the resilience of cities in the event of physical, social, and economic stresses (100 Resilient Cities 2016).

From the end of 2017 to the beginning of 2018, the City of Seattle developed a Resilience Strategy. The aim of the Resilience Strategy is to "give Seattle a strong foundation to build resilience and to spur coordination and resilience thinking" (Office of Sustainability and Environment 2018). The Strategy itself is not complete, but information from the Seattle Resilience Workshop Report from October 2016 will be used to gain insight on the relevance of green infrastructure ecosystem services in Seattle. In addition, I analyzed the following five plans and reports to assess Seattle's priorities for green infrastructure ecosystem services:

1. Seattle Comprehensive Plan: A Plan for Managing Growth 2015 – 2035

   This 20-year policy plan is guided by 4 core values: community, environmental stewardship, economic opportunity and security, and social equity. It covers 14 elements, such as environment and transportation, and provides goals and policies for each of them. Many of these goals and policies touch on the benefits of green infrastructure.

2. Moving the Needle: Environmental Progress Report (2017)

   This report focuses on an overview of what the City has accomplished and opportunity areas for the future in terms of protecting and enhancing 8 broad environmental topics. The accomplishments mentioned in this report help to quantify the impact green infrastructure ecosystem benefits have provided to Seattle thus far.

3. Seattle Forest Ecosystem Value Report (2012)

   This report provides an analysis of structure, function, and economic benefits of urban forests in Seattle. It focuses on 4 urban forest functions and values: pollution removal, carbon storage and sequestration, residential building energy savings, and replacement value. Each ecosystem function is given an estimated value for their services, which will be expanded on in the following section.

4. Urban Forest Stewardship Plan (2013)

   The purpose of the plan is for the City to recognize the value and ecosystem services of urban forests, including air and water pollution mitigation, habitat for wildlife, stormwater runoff mitigation, and health benefits. In 2007, the Urban Forest Management Plan set a goal to increase Seattle's tree canopy cover to 30% by 2037 (UFSP). The 2013 Urban Forest Stewardship Plan is the first update of that plan, and includes goals, strategies, and actions that relate to the ecosystem benefits of green infrastructure.

5. Carbon Neutral Climate Ready: Preparing for Climate Change (2017)

   This report provides focused actions on addressing the City's climate preparedness through infrastructure and services.

The following section identifies specific actions recommended by these plans and reports that relate to green infrastructure and its multifunctional benefits.

RELEVANCE OF GREEN INFRASTRUCTURE ECOSYSTEM SERVICES

Overview

This section discusses three points for each ecosystem service: 1) the background of what the main environmental or social issue is, 2) how green infrastructure benefits mitigate that issue, and 3) what the relevance is to Seattle.

Social vulnerability

Background

Disparities in greenery in low-income minority neighborhoods is a topic widely discussed within urban green space, public health, and environmental justice studies. “Park poverty” is a social justice issue (Wolch, Byrne, and Newell 2014) that many cities still face today where low-income, minority neighborhoods are less likely to have access to green spaces within a reasonable walking distance and in terms of total green area (Heynen 2006). Literature have shown that more vegetation can interact with factors that influence social vulnerability such as lowering crime rates (Kuo and Sullivan 2001). Improving access to green spaces in vulnerable neighborhoods also enhances community resilience (Cutter 1996). However, increasing green infrastructure in low-income and minority neighborhoods needs to be done with policies in place to carefully ensure that they do not lead to green gentrification (Wolch, Byrne, and Newell 2014). Therefore, including social vulnerability into any green infrastructure analysis is important because it investigates any existing inequities in access to green space.

Relevance to Seattle

In every Seattle plan or report mentioned in the previous section, social equity is identified as a core goal in one way or another. The Comprehensive Plan itself has 4 major goals, one of which is social equity. Seattle is known for its growing economy, but like other cities past policies reflecting systemic racism and class inequities impacted the distribution of benefits. The

Seattle Resilience Strategy states that several well-being indicators (such as education, income, and unemployment rates) show inequalities by race and ethnicity.

The City has acknowledged that the social equity issue exposes minority and low-income populations to higher risks from environmental stressors (Office of Sustainability and Environment 2018; City of Seattle 2017). In 2015, the Equity and Environment Initiative (EEI) was launched to build community capacity within disadvantaged populations and engage them with government support to advance environmental justice (Office of Sustainability and Environment 2018). This initiative identified EEI geographic focus areas (Figure 3) based on the following criteria: less than 20% tree canopy cover, minority populations, low-income populations and people with limited-English proficiency (City of Seattle 2017).

EEI areas and other neighborhoods of distressed communities need to be prioritized to ensure they are receiving benefits and support from the City's infrastructure and services to build a high quality of living. Some of these benefits include ecosystem services provided by green infrastructure. The inclusion of social vulnerability into the analysis will give priority to areas that face disparities in services that impact their socioeconomic status.

Stormwater runoff mitigation

Background

Change in land cover from pervious to impervious leads to changes in the quality and quantity of stormwater runoff (Brabec, Schulte, and Richards 2002; USDA-NRCS 1986; Whitford, Ennos, and Handley 2001). Not only does increased quantity of stormwater runoff lead to increased amounts of pollutants carried, but it also causes combined stormwater overflows in cities whose sewer system cannot handle runoff above a certain threshold (Droguett 2011). Untreated stormwater runoff and combined sewer overflows is the main source of pollution for waterways in the United States (USEPA 2009). In addition to pollution from sewers, if a watershed is about 10% impervious, the stream quality declines below acceptable levels (Washington State Department of Ecology 2012; Brabec, Schulte, and Richards 2002). The decrease in water quality from runoff is because water does not percolate into the soil for treatment before reaching waterbodies (Brabec, Schulte, and Richards 2002). Therefore, the issue with stormwater runoff includes the volume and inability for sewer systems to handle it, as well as untreated contaminated water reaching water ecosystems.

Traditionally cities manage stormwater through gray infrastructure which includes the sewer system (Droguett 2011). However, as infrastructure ages and cities continue to grow, existing structures are often not able to handle the amount of sewage and stormwater that needs to be captured. They are also expensive and inconvenient to replace (Droguett 2011). A popular alternative solution is using green infrastructure to aid in infiltration and treatment of stormwater runoff (Droguett 2011). Studies have shown that green infrastructure reduces run off volume through decreasing water velocity to encourage infiltration, and increased evaporation and evapotranspiration from plants(Hatt, Fletcher, and Deletic 2009). Additionally, infiltration of water into soil treats the stormwater and removes sedimentation and pollution (Hatt, Fletcher, and Deletic 2009).

Relevance to Seattle

The importance of greening impervious surfaces to reduce stormwater impacts through slowing water velocity and increasing permeability is mentioned in the Seattle Forest Ecosystem Value Report and Seattle's Comprehensive Plan. Previous Seattle-based studies have shown that tree canopy covering impervious surfaces can reduce runoff by about 27% (Green Cities Research Alliance 2012).

In addition to controlling the volume of stormwater runoff, the 2017 Environmental Progress Report states that stormwater runoff also pollutes the Puget Sound and Duwamish River. From 2014 to 2016 there was a 20% increase in removal of pollutants, largely due to street sweeping. In 2016, green stormwater infrastructure allowed the City to treat 192 million gallons of polluted stormwater which otherwise would have flowed into the surrounding water bodies (City of Seattle 2017).

However, the City still faces issues with combined sewer overflows (CSOs) and currently does not meet the performance standard of the National Pollutant Discharge Elimination System (NPDES) Permit of an average no more than one overflow event at each CSO outfall per year (Seattle Public Utilities 2009). In 2010, the City had 94 CSO outfalls and had reduced overflows from 24 of them over two decades (Seattle Public Utilities 2009). By 2016, Seattle reduced the number of CSO outfalls to 85, but 47% had an average CSO frequency higher than 1 event per year between 2012 to 2016 (Seattle Public Utilities 2017), higher than the acceptable NPDES performance standard. A total of 314 CSO discharge events occurred in 2016, and over 50% of these events occurred at five specific CSO outfalls (Seattle Public Utilities 2017).

Thus, it is not surprising that the Comprehensive Plan has several goals and policies that address the issue with stormwater runoff. Vegetative cover and green stormwater infrastructure was mentioned several times as a solution to mitigate stormwater runoff and reduce environmental impacts to surrounding water bodies (Office of Planning & Community Development 2015).[1]

Stormwater runoff mitigation is an ecosystem service provided by green infrastructure that the City of Seattle recognizes; it is relevant to include in this analysis to determine areas of need for these ecosystem benefits.

Air pollution mitigation

Background

In 2014, the World Health Organization (WHO) estimated that exposure to ambient (outdoor) air pollution was responsible for 4.2 million deaths per year (World Health Organization 2018b). In 2018, this estimate has increased to 7 million per year (World Health Organization 2018c). 9 out of 10 people are exposed to ambient air pollution, and this exposure is responsible for 1 in 9 deaths worldwide (World Health Organization 2018a). People living in urban areas tend to be exposed to higher concentration of particulate matter (Larondelle and Lauf 2016), increasing their risk of heart disease, lung cancer, and respiratory diseases (World Health Organization 2018c). Of those people, air pollution data from urban areas with monitors have shown that 80% of people in urban areas are exposed to air pollution levels above WHO's limits (World Health Organization 2018c). Literature strongly supports that particulate matter (PM), nitrogen dioxide, sulfur dioxide, and ozone are the main culprits in diminishing public health (World Health Organization 2018b), especially small particles (less than 10 microns)

[1] Goals and policies referenced: LU215, BL-P3, EG3, E8.1, R-EP1

which can enter the bloodstream through the respiratory system (Larondelle and Lauf 2016). This disproportionately affects low and middle-income countries where 97% of cities with a population of more than 100,000 people do not meet WHO air quality standards (World Health Organization 2018c). Within cities themselves, EPA scientists found in a study that income and race/ethnicity influenced exposure to air pollution (Mikati et al. 2018). Exposure to PM2.5 was found to be 1.35 times higher for those in poverty compared to the whole population, and 1.8 times higher for minority populations (Mikati et al. 2018).

Vegetation and green infrastructure improves the air quality by reducing nitrogen dioxide and particulate matter in air (Pugh et al. 2012). This can be through uptake of particles, or deposition of particles onto the leaves of trees and shrubs. A study by Lovasi et al (2008) found a positive correlation between presence of street trees and lower child asthma rates (Lovasi et al. 2008). Therefore, mitigating air pollution with greenery reduces human exposure to harmful particles, which is expected to improve public health.

Relevance to Seattle

Green infrastructure helps to mitigate air pollution through deposition of particulate matter on leaves and absorption of pollutants (Green Cities Research Alliance 2012). The Seattle Forest Ecosystem Values Report (2012) estimates the value of pollution removal by urban forests in Seattle to be $5.6 million annually. These estimates take into account ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide, and particulate matter less than 10 microns.

Despite the estimated pollution removal benefits of urban forests in Seattle, certain neighborhoods face higher exposure levels than others. For example, residents living in neighborhoods close to hazardous sites have higher exposure to toxins (100 Resilient Cities 2016). Another major source of air pollution in Seattle is transportation; it is the largest single cause of air pollution in Seattle (City of Seattle 2017). The 2017 Environmental Progress Report states that within the United States, Seattle ranks third in measured nitrogen dioxide in the atmosphere, a pollutant that is a result of road traffic. For both air pollution sources, the residents who live closest to hazardous sites or heavily trafficked major roads are from minority and low-income populations. Therefore, addressing air pollution mitigation is a key recommendation and goal for Seattle as mentioned in the Environmental Progress Report (2017) and Seattle's Comprehensive Plan (2015 – 2035).

There are several goals within the Comprehensive Plan that highlights the importance of air pollution mitigation to the City. Under the transportation section, one of the goals (TG21) is to "reduce or mitigate air, water, and noise pollution from motor vehicles" (Office of Planning & Community Development 2015). The land use section also addresses regulation of air emissions from industrial and commercial activities to protect Seattleites from the negative health impacts of air pollutants (Office of Planning & Community Development 2015).[2] Several goals and policies mention the use of green infrastructure and natural systems to mitigate air pollution (Office of Planning & Community Development 2015).[3] Lastly, the comprehensive plan calls to "coordinate with other city, county, regional, state, and federal agencies to pursue opportunities for air improvement", as well as engage the "community, property owners, and public agencies [to identify] tools to improve air quality" (Office of Planning & Community Development 2015).[4]

It is evident that air pollution mitigation is a goal that Seattle wants to address, whether through green infrastructure and/or coordination between stakeholders.

[2] Goals and actions referenced: LU46
[3] Goals and actions referenced: EG3, E22
[4] Goals and actions referenced: T55, BL-P38

Carbon sequestration

Background

Cities house more than 50% of the world population, and the rise in urban population is increasing carbon emissions from energy use and transportation (Whitford, Ennos, and Handley 2001). Carbon emissions can be mitigated through carbon sequestration: the uptake of carbon from the atmosphere by vegetation (Larondelle and Lauf 2016). For example, carbon dioxide is one of the main greenhouse gases that negatively impacts climate change, but it is readily sequestered from the atmosphere and used by plants for growth (Baur et al. 2015). Several studies have examined how trees and vegetation can be carbon sinks to reduce the amount of carbon emitted from human activities. A review of urban trees ecosystem services research in Chicago found that in 1991, it was estimated that 5575 metric tons of air pollutants were removed by urban trees, a service whose estimated value is $9.2 million (McPherson et al. 1997). A 10% increase in tree cover can save annual energy costs for heating and cooling by $50 to $90 per building (McPherson et al. 1997). Therefore, carbon sequestration is an important ecosystem service provided by green infrastructure not just to remove carbon from the atmosphere, but also by reducing energy costs with increased tree canopy cover.

Relevance to Seattle

Green infrastructure, especially trees, are known to reduce atmospheric carbon dioxide through carbon storage and sequestration (Green Cities Research Alliance 2012). Not only does the urban forest in Seattle store an estimated 2 million metric tons of CO_2, but it also sequesters 140,000 metric tons of CO_2 annually (Green Cities Research Alliance 2012). This amount of stored and sequestered carbon has been estimated to be valued at about $11.7 million (Green Cities Research Alliance 2012; City of Seattle 2017). Additionally, the total greenhouse gas emissions in Seattle peaked in 2008 and has been decreasing ever since even with population growth (City of Seattle 2017).

Even with the decrease in carbon since 2008 and one of the lowest per person carbon emissions in the country, Seattle still has work to do to reach the goal of carbon neutrality by 2050 (Office of Planning & Community Development 2015). One of the strategies for reaching this goal is to "enhance urban forests to…absorb carbon dioxide" (Office of Planning & Community Development 2015).[5] Therefore, carbon sequestration is an ecosystem service that is very relevant to Seattle's urban planning and will be included in this analysis.

[5] Goals and actions referenced: E22

Urban Heat Island Effect Mitigation

Background

Urbanization, and the subsequent change of the physical landscape as population and economic growth expands, affects the living environment and well-being of urban residents. One way urban areas are affected is through land cover change and the urban heat island (UHI) effect. Urbanization leads to expansion of impervious surfaces such as buildings and roads which usually takes over natural vegetation (Aflaki et al. 2017; Xu 2007). Without the cooling effect of transpiration from vegetation, the higher absorption of solar radiation by impervious surfaces causes an increase in land surface temperature (Weng 2001; Xu 2007). The result is an urban heat island effect where urban areas tend to have relatively higher temperatures compared with surrounding rural or more vegetated areas (Weng 2001; Kardinal Jusuf et al. 2007b). This temperature difference may only be about 1 degree Celsius, but can be intensified in urban areas depending on the weather (Weng 2001; Bowler et al. 2010; Meerow and Newell 2017). Furthermore, the additional heat stress on human health can lead to an increase in heat-related morbidity and mortality (Scherer et al. 2013).

As the UHI effect intensifies with climate change and reduction of greenery in cities, planners need to assess how land use and land cover can mitigate rising temperatures (Kardinal Jusuf et al. 2007a). The presence of urban trees can mitigate the UHI effect through transpiration (McPhearson, Kremer, and Hamstead 2013). Lower temperatures within cities not only improves livelihoods, but also requires less electricity for cooling, helping cities to reach climate resiliency goals (Kardinal Jusuf et al. 2007b; Roth and Chow 2012; Madureira and Andresen 2014). Some solutions planners have adopted include innovative landscape planning such as green roofs and large urban parks (Aflaki et al. 2017).

Relevance to Seattle

In the City's Preparing for Climate Change (2017) report, a climate model showed that for all future scenarios run, an "increase in annual and seasonal temperatures for the Puget Sound region" was observed. The urban heat island effect may play a role in exacerbating the increase in temperatures in Seattle (relative to rural areas) (Office of Sustainability and Environment 2017). Seattle City Light conducted a study on the Seattle metropolitan area and found that by 2050, it is likely to have 18 more days (+/- 6 days) with temperature above 86F. In addition to impervious surfaces and the lack of vegetative cooling that lead to the urban heat island effect, high energy use in urban areas from automobiles, heating/cooling, and ventilation also increases urban temperatures (Office of Sustainability and Environment 2017; Green Cities Research Alliance 2012; Raymond 2016).

Urban forests and other greenery mitigates high temperatures through evaporative cooling and shading (Green Cities Research Alliance 2012). This can lead to reduced energy use by an amount equivalent to $5.9 million (Green Cities Research Alliance 2012). By reducing energy use, this also reduces the heat produced by heating and cooling systems.

The City of Seattle recognizes the value of using green infrastructure to mitigate the urban heat island effect in the Climate Ready strategy report: "mitigate the urban heat island effect through programs that cool the urban environment, including planting and maintaining trees, increasing green space and employing green infrastructure, particularly in EEI focus areas" (Office of Sustainability and Environment 2017). Therefore, the inclusion of urban heat island mitigation in this analysis is relevant to the City of Seattle's climate and sustainability goals.

Habitat Connectivity and Buffers

Background

Urbanization has not only caused the urban heat island effect, but also fragmented natural wildlife habitats in an urban landscape (Ahern 2011). This not only reduces the area of habitat for wildlife, but also limits them from moving and interacting with a larger pool of diversity. Additionally, habitat patches expose wildlife to the edge effect which can be detrimental to biodiversity, further reducing ecosystem services and benefits that come with a strong biodiverse habitat (Cardinale et al. 2012). The ability for wildlife to interact with a larger pool of individuals within their species allows for greater biodiversity and conservation of species (Kong et al. 2010). To combat the negative consequences of habitat fragmentation and the edge effect in urban areas, habitat connectivity is a way to provide corridors for animals to traverse and protect biodiversity (Bolger et al. 2000). Green infrastructure within urban areas can be designed to be corridors that provide wildlife with connections to other habitat patches.

Relevance to Seattle

The urban forest within Seattle also provides habitat for wildlife to find food and shelter (Green Cities Research Alliance 2012). Protection of wildlife from human interference and fragmentation is acknowledged in Seattle's goals for improving the natural environment within an urban environment. For example, in the Urban Forest Stewardship Program (2013), one of the long-term actions proposed is to "develop cross-departmental measures and deliverables for the reduction of fragmentation effects on wildlife and urban forests".[6]

The Comprehensive Plan also touches on many aspects of conserving and protecting Seattle's urban ecosystems and habitat, such as establishing wildlife corridors and explore publc-private partnerships to improve habitat in the City's environmentally critical areas so that

[6] Goal or action referenced: U20

these habitats are healthy for native wildlife.[7] Identifying areas of need for habitat connectivity in this analysis will help the City reach some of these actions and goals.

Access to Green Space

Background

Access to green spaces has been shown to positively influence health and wellness (Meerow and Newell 2017; Kremer, Hamstead, and McPhearson 2016; McPhearson, Kremer, and Hamstead 2013; Madureira and Andresen 2014). Studies have shown that having access to green spaces holds recreational and aesthetic values for the residents within walking distance (Tzoulas et al. 2007; Priego, Breuste, and Rojas 2008). Proximity to green spaces offers potential recreational activities which encourages physical activity and combats obesity (Younger et al. 2008). Having access to green spaces is not just beneficial for physical health, but also mental health (Larondelle and Lauf 2016). Exposure to nature and greenery can decrease aggressive behavior, reduce mental fatigue, and strengthen communities and neighborliness (Droguett 2011).

Relevance to Seattle

According to the Seattle Resilience Strategy, exposure to open space and opportunities for recreation was identified by 40% of respondents as what they love most about Seattle. However, access to open space for outdoor recreation is not equally distributed among residents. Like any other city, Seattle has neighborhoods with a high percentage of minority and low-income populations where there is an inadequate access to green space (Office of Sustainability and Environment 2018; City of Seattle 2017). The 2017 Environmental Progress report shares that areas with a lower percentage of tree canopy cover are where minorities and

[7] Goal or action referenced: LU226, LUG38

low-income populations tend to live. In 2016, the average tree canopy cover of Seattle was 28%, yet EEI areas only had 20% (City of Seattle 2017). This is important because these populations are not sharing in the health and community benefits of access to green space.

The Comprehensive Plan addresses the need for providing accessible parks and open spaces, especially within urban villages where growth will be concentrated.[8] The goals in the Comprehensive Plan provide the reasoning for why access to green space is relevant and included in this analysis.

[8] Goals and actions referenced: UVG14, LUG8

SUMMARY

Multiple City plans and reports identify goals, strategies, and actions that directly relate to the use of green infrastructure for their ecosystem services. This chapter clearly shows that the ecosystem services selected for this analysis are highly relevant to green infrastructure planning in Seattle.

Understanding the spatial interaction between these ecosystem services is useful for planners to decide which green infrastructure locations can meet multiple goals or purposes. Planning with the multifunctionality of green infrastructure in mind requires studying the connectivity and spatial distribution of ecosystem services (Hansen and Pauleit 2014). The next chapter analyzes multi-criteria GIS models that look at the spatial relationship between ecosystem services.

CHAPTER 4 //

SPATIAL MULTI-CRITERIA DECISION ANALYSIS (S-MCDA) MODELS

OVERVIEW

By understanding the connectivity and overlapping needs for ecosystem services on a spatial level, planners can identify which locations for green infrastructure will provide for multiple specific ecosystem services. For example, a question planners can ask is: "Where can green infrastructure be sited so that it mitigates the urban heat island effect and air pollution?". To answer this question, synergies and tradeoffs between ecosystem services need to be researched and analyzed. Synergies are pairs of ecosystem services where for example, a high need for one ecosystem service aligns with a high need for another ecosystem service. It is an ideal situation to have multiple synergies where green infrastructure is sited as it improves more than one ecosystem service need. Tradeoffs between ecosystem services indicate a negative correlation of needs. For example, a low need for one ecosystem service aligns with a high need for another ecosystem service, thus green infrastructure is sited based addressing one ecosystem service while losing another.

Understanding synergies and tradeoffs between pairs of ecosystem services to maximum benefits for humans is an objective of green infrastructure planning (Hansen and Pauleit 2014). To study green infrastructure ecosystem services and the associated synergies and tradeoffs, a multi-criteria decision analysis (MCDA) model can be utilized. This chapter is broken up into 3 sections: 1) defining MCDA models and how a spatial element bolsters such analyses, 2) a methodological literature review of 9 S-MCDA models related to green infrastructure ecosystem benefits, and 3) a review of how ecosystem services are measured in the 9 S-MCDA models.

Defining Multi-Criteria Decision Analysis (MCDA) Models

Multi-Criteria Decision Analysis (MCDA) Models

Multi-criteria decision analysis (MCDA or MCA) allows researchers to analyze multiple variables that may not always be compared in studies, making it useful to evaluate socioecological issues for a single objective (Martinez-Alier, Munda, and O'Neill 1998; Giordano and Riedel 2008). MCDA is also referred to as "stacking", where researchers overlay variables to better understand any existing relationships (McPhearson, Kremer, and Hamstead 2013). Therefore, MCDA is useful in analyzing trade-offs and synergies between green infrastructure ecosystem services and clarifying the complexities of ecosystem services to planners (Grêt-Regamey et al. 2013). It serves as a tool for data-driven decision making by analyzing different priority scenarios with the same multiple social, economic, or environmental variables (Giordano and Riedel 2008). From a technical viewpoint, MCDA "involves scaling, ranking, and aggregating variables through weighted optimization procedures" (Kremer, Hamstead, and McPhearson 2016).

Spatial MCDA (S-MCDA)

Spatial MCDA models are used to evaluate multiple variables at some spatial scale, thus merging GIS and MCDA into one powerful too (Zucca, Sharifi, and Fabbri 2008). S-MCDA allows for integration of geographic identifiers and distribution of variables in the analysis to see how results react spatially (Kremer, Hamstead, and McPhearson 2016). The multifunctionality of green infrastructure is an example of how S-MCDA can be used for effective management and location of green infrastructure planning (Madureira and Andresen 2014). Mapping the spatial patterns of ecosystem services and their overlapping needs allows for a closer examination of where investments can be most efficient (Meerow and Newell 2017). Such information and results will be valuable for spatial land-use planning (Lennon 2015) and maximizing green infrastructure services for residents (Crossman et al. 2013).Therefore, to better understand how researchers have used S-MCDA models to analyze multiple green infrastructure ecosystem services, a literature review was conducted to determine common methodology, ecosystem services, and gaps in current analyses.

Existing S-MCDA Models of Green Infrastructure Ecosystem Services: Methodological Review

Introduction

For this literature review, I used search terms relating to green infrastructure, ecosystem services, multi-criteria analysis, and spatial analysis. I looked for articles that conducted a S-MCDA of green infrastructure ecosystem services to identify potential green infrastructure sites. I analyzed the models based on the modelling approach, location and scale, tradeoffs and synergies analysis, weighting, involvement of stakeholders, ecosystem services inclusion, and land use suitability factor inclusion. From this review, I determined that common gaps in past analyses is the lack of stakeholder inclusion, social vulnerability, and inclusion of spatial statistics for tradeoff and synergies analysis and a land use suitability analysis. There is a need for S-MCDA of green infrastructure ecosystem services that includes these factors. Based on this, I aim to create an S-MCDA model that includes social vulnerability to address disparities in green space access, includes weighting scenarios by ecosystem service, includes land use and ownership data, and conducts a spatial statistic tradeoff and synergies analysis. Such models can be helpful for a more holistic planning process related to green infrastructure, and the developed model should be accessible and available for local governments to use.

Background

The use of combined GIS and MCDA models is well established particularly in studies focusing on land suitability analysis (Chakhar and Mousseau 2008). GIS technology allows for spatial analysis to inform decision-making, while MCDA takes into account multiple factors of interest to allow for evaluating and prioritizing decisions (Malczewski 2006). Geospatial data is integrated into the MCDA framework as layers or factors which stakeholders determine as a set of relevant evaluation criteria for the topic in question (Malczewski 2004). Examples of using spatial multi-criteria decision analysis (S-MCDA) for suitability modelling include watershed planning and management, environmental and urban planning, and participatory planning (La Rosa et al. 2014). In this paper, the aim is to use S-MCDA for green infrastructure and greenspace planning purposes. There is growing interest in the multifunctionality of green infrastructure, and an increasing need to include additional ecosystem services in green infrastructure planning (Meerow and Newell 2017). Therefore, modelling the interactions of green infrastructure ecosystem services is timely. This chapter aims to review existing studies that use S-MCDA for green infrastructure or green space planning purposes. This systematic review begins with a search for articles that have conducted a S-MCDA of green infrastructure ecosystem services. After selecting relevant articles, model components and gaps are analyzed and discussed.

Literature Review Methodology

For this review, I used the following three databases to search for relevant articles: Web of Science, ScienceDirect, and Google Scholar. I used a combination of words for the following subjects: multifunctional, green infrastructure, multi criteria evaluation, and spatial analysis, and searched for articles published after 1997. The exact search terms can be found in Table 1. In Web of Science, my first search (see Table 2 for exact search phrases) produced 13 results, 1 of which was partially relevant, so I decided to include more search terms to produce more relevant results. My final search terms (Table 2) resulted in 53 articles, 7 of which were relevant. In ScienceDirect, my first search using the expert search interface resulted in over 10,000 results. I narrowed this down by modifying my search term to only look for articles with (multi criteria analysis OR suitabl*) in the title, abstract, or key words. I ended up with 217 articles, 11 of which were relevant, and of these 2 were duplicates from the Web of Science search. In Google Scholar, there were 712 results, 21 of which were relevant.

I selected articles as relevant if they included more than two green infrastructure or green space ecosystem services in their analysis. As a result, 9 articles were analyzed for their spatial multi-criteria analysis model.

Table 1: Search terms used for this literature review

Multifunctional	Green Infrastructure	Multi Criteria Evaluation	Spatial Analysis
Ecosystem service*	"Green infrastructure"	Multi criteria analysis	Spatial
Multi functional*	Urban green* space*	Suitability	GIS
Benefit*			

Table 2: Specific search terms used by database

Search #	Web of Science	ScienceDirect	Google Scholar
1	TS=(ecosystem service OR multifunctional OR benefits) AND TS=(green infrastructure OR urban green spaces) AND TS=(multi criteria evaluation OR suitability analysis) AND TS=(spatial analysis OR GIS OR model)	green infrastructure OR green space AND benefit* OR ecosystem service* OR multi function* AND spatial AND multi criteria analysis OR suitabl*	("ecosystem service" OR "multifunctional" OR "multi-functional" OR "benefits") AND ("green infrastructure" OR "green spaces" OR "urban green spaces") AND ("multi criteria evaluation" OR "multi-criteria evaluation" OR "suitability analysis") AND ("spatial analysis" OR "GIS" OR "model")
Results	**13**	**11,713**	**712**
2	TS=("green infrastructure" OR urban green* space*) AND TS=("ecosystem service*" OR multi functional* OR benefit*) AND TI=(multi criteria analysis OR suitability OR spatial)	(green infrastructure OR green space AND benefit* OR ecosystem service* OR multi function* AND spatial) and TITLE-ABSTR-KEY(multi criteria analysis OR suitabl*)	
Results	**53**	**217**	

Methodology Analysis of S-MCDA Models

After reviewing complete manuscripts of relevant articles, 9 models were extracted for a systematic review of the S-MCDA models used. Models were reviewed on their modelling approach, location and scale, inclusion of spatial trade-offs and synergies, weighting between ES, stakeholder participation in weighting, number of ES included, and number of suitability factors included in the analysis.

Modelling Approach

All 9 models use some sort of suitability analysis to aggregate and stack the ecosystem services included in the analysis. Only one model (Madureira and Andresen 2014) used suitability averages, while the rest used suitability aggregation (Table 3). Madureira and Andresen (2014) calculated the average of the two ecosystem services they had mapped out to have a suitability output of spatial priority areas for green infrastructure planning. Rather than taking the average of stacked ecosystem services ranking, the other 8 models added up the normalized values assigned. The suitability aggregation method makes more sense when finding out priority areas with a higher number of ecosystem services needed. So, when creating a S-MCDA model, this approach will be used for the suitability analysis.

Table 3: Modelling approaches of the 9 S-MCDA models reviewed

Modelling Approach	Number of Models	Source
Suitability aggregation (ADD)	8	Meerow and Newell (2017) Kremer, Hamstead, and McPhearson (2016) McPhearson, Kremer, and Hamstead (2013) Holt et al. (2015) Larondelle and Lauf (2016) Zucca, Sharifi, and Fabbri (2008) Giordano and Riedel (2008) Gül, Gezer, and Kane (2006)
Suitability averages (MEAN)	1	Madureira and Andresen 2014
Pathway analysis	1	Giordano and Riedel (2008)
Hotspot/Cluster Analysis	5	Meerow and Newell (2017) Kremer, Hamstead, and McPhearson (2016) McPhearson, Kremer, and Hamstead (2013) Madureira and Andresen (2014) Holt et al. (2015)
Site Selection	2	Zucca, Sharifi, and Fabbri (2008) Gül, Gezer, and Kane (2006)

Location and Scale

The area of interest for all 9 models reviewed focused on an urban environment at the city scale. Location focus across the models were not confined to the United States as only 3 of the models studied cities in the US. Other locations include: Porto, Portugal; Sheffield, UK; Berlin, Germany; Province, Italy; Sao Paolo, Brazil; and Isparta, Turkey.

Despite the application of the S-MCDA models on cities, the spatial unit for analysis varied across the 9 studies from 1m pixels to the Census Tract level. Only 2 of the studies produced outputs for different scales for comparison.

Holt et al. (2015) mapped ecosystem services in Sheffield, UK at 3 spatial levels with the reasoning that decision-makers will base plans on meaningful spatial units such as the "social and or environmental composition of a city". To compare between a standard grid versus meaningful spatial units, Holt et al. (2015) used the following 3 spatial levels: 1) 500 m grid, Output Area (OA), and HECA (South Yorkshire Historic Environment Character Area). OAs were derived from social homogeneity based on UK 2001 Census data. HECA polygons represented urban design homogeneity. Holt et al. (2015) found that the distribution of hotspots differed slightly across the 3 spatial units. Although there was a general trend across the spatial units for high and low spots, there were still differences in location and strength of correlation between ecosystem services across spatial scales. This could influence decision-making, and Holt et al. (2015) recommended that spatial units for modelling should link to what is being asked. For example, if decision-makers or researchers seek to gain more understanding about human-environment and socio-ecosystem services, a spatial unit based on social data should be used (Holt et al. 2015).

Larondelle and Lauf (2016) assessed the demand and supply of various ecosystem services at the block and neighborhood level in Berlin, Germany, emphasizing that information at different scales can be helpful for planners to address environmental and social issue. As with any aggregation of data to a larger spatial unit, Larondelle and Lauf (2016) found that aggregating from the block level to neighborhood level loses some level of detail. However, having results at both spatial scales is advantageous for different planning needs. The authors point out that results at a fine scale helps illustrate ecosystem services for the immediate surrounding citizens living in those blocks, something which is needed for well-informed decision-making. At a coarse scale, this makes it easier to compare results to socio-economic data that is accurate only at a neighborhood scale, which is also a scale where political action and support is more effective (Larondelle and Lauf 2016).

Drawing from these two models, a multi-scale S-MCDA to map the multi-functionality of green infrastructure would be more beneficial to target various levels of green space planning and decision-making. However, due to time limitations this report will only focus on one spatial scale; further research based on this report can built on these results and include a multi-scale analysis.

Trade-offs and Synergies

A benefit of conducting a S-MCDA for suitability of green infrastructure where ecosystem services are needed is not just to overlay various benefits, but also to compare and contrast the location of ecosystem service to one another (McPhearson, Kremer, and Hamstead 2013; Meerow and Newell 2017). Not all suitability locations will be providing all services included in the analysis; there may be trade-offs between services, and there may be synergies where spatial location of two ecosystem services are correlated. Therefore, it is important to understand and analyze the trade-offs and synergies between ecosystem services when conducting a S-MCDA to gain a better understanding of how these services interact with each other. The interaction of these services will influence decision-making processes for site selection and development of greenspace planning.

Analysis of tradeoffs and synergies can be quantitative or visual. Of the 9 models analyzed in this review, 5 studies included some aspect of spatial trade-off and synergies ecosystem services analysis. Meerow and Newall (2017) and Holt et al. (2015) both used regression analyses to extract any significant correlations between the ecosystem services included in their model. Using Pearson's correlation coefficient, Meerow and Newall (2017) found that high priority stormwater runoff reduction areas are significantly negatively correlated to areas that need landscape connectivity. This tradeoff could be difficult to manage in a planning process if a city seeks to address both issues with green infrastructure. However, in Holt et al's (2015) Spearman's rank correlation coefficient analysis, they found a statistically significant positive correlation between habitat provision and runoff reduction at all spatial scales. The disparity in these results point to the different factors used to quantify habitat resilience, and the difference in location and scale. A limitation for conducting this type of analysis is that it does not distinguish spatial correlations. Therefore, tradeoffs and synergies will vary depending on model inputs and location and should be analyzed for any S-MCDA applied to a study. Within a city or area of study, there may be areas where pairs of ecosystem services are positively correlated, and other areas where they are not. Visually assessing tradeoffs and synergies provides a simple way to infer the spatial aspect of ecosystem services relationships.

The other 3 models visually observed different weighting scenarios or ecosystem service maps to glean any spatial trends between services. The limitation for this is that relationships cannot be quantified as significant, but it provides a first step towards identifying possible patterns between ecosystem services. For example, Madureira and Andresen (2014) mapped two ecosystem services: need for urban heat island mitigation, and access to green spaces in Porto, Portugal. The resulting maps illustrate synergies between these two ecosystem services in the western and southern part of the city. However, there are tradeoffs between the two services in the northern part and eastern part of the city. Therefore, there is a need to include both quantitative analysis and spatial analysis of ecosystem service interactions. One way of doing this is including spatial statistics as a part of S-MCDA models. The inclusion of this into future models is crucial as local governments currently do not account for the interactions between ecosystem services (Meerow and Newell 2017).

Weighting

Weighting of ecosystem services of green infrastructure is a way to capture the varying valuation of ecosystem services in a specific location. For example, stakeholders in a location facing issues with combined sewer overflows and flooding, may put more emphasis on the stormwater runoff reduction service of green infrastructure above other ecosystem services. Differing weights across ecosystem services can influence the resulting suitability map. Of the 9 models reviewed, 5 included some kind of weighting between the ecosystem services included in their analysis. Kremer, Hamstead, and McPhearson (2016) was the only study that compared different weighting scenarios based on priorities of government agencies, while the other models based their weights on direct stakeholder participation.

Kremer, Hamstead, and McPhearson (2016) analyzed four weighting scenarios for New York City: 1) equal weighting across all ecosystem services, 2) higher weighting for stormwater absorption, other ecosystem services weighted equally, 3) ranking of ecosystem services with stormwater absorption as the top priority, 4) single criteria-stormwater absorption. The authors found that the aggregated ecosystem services spatial distribution pattern changed across the 4 scenarios. For example, a map of the mathematical difference between scenario 1 and scenario 4 was produced to illustrate the difference in ecosystem services distribution under different valuations.

Although Kremer, Hamstead, and McPhearson (2016) did refer to NYC agencies to determine ecosystem services priorities, they did not include the ecosystem services valuation of the community and residents. The 4 studies that directly involved stakeholders did so through various methods. Meerow and Newell (2017) held a meeting with stakeholders from government agencies, nonprofit organizations, and community development organizations. Zucca, Sharifi, and Fabbri (2008) and Giordano and Riedel (2008) directly involved experts to determine ranking of ecosystem services included in the analysis. Gül, Gezer, and Kane (2006) used survey results from a previous study that investigated resident and greenspace management expert's priorities, as well as their own survey of greenspace management experts.

Through the evaluation of various weighting strategies, a scenario-based S-MCDA that includes stakeholder participation in defining priorities will be central to the model developed in this thesis. Designing a user-friendly interface to allow for stakeholder influenced scenario modelling will enable stakeholders without the GIS technical capabilities to analyze the effects of differing priorities in an area and inform green space planning decisions.

Ecosystem Services Inclusion

The minimum number of ecosystem services included in a single study was 2, and the maximum was 7 (see Table 4). The decision to include various ecosystem services was broadly based on 3 key factors:

1. Literature review
    a. Key urban related ecosystem services
    b. Key environmental and social green infrastructure ecosystem services
2. Stakeholder priorities
    a. Existing decision-making inclusion of ecosystem services
    b. Expert opinions
    c. Residents
    d. City plans
3. Data
    a. Data availability
    b. Ecosystem services quantification feasibility

The green infrastructure ecosystem service that was included in all 9 models was access to green space. In evaluating models for access to green space, this included any cultural or health factor relate to and a result of people accessing the green space. Inclusion of reducing urban heat island effect and increasing habitat resilience (or landscape connectivity) were the next top two ecosystem services that were included in the 9 models. The bottom two ecosystem services that were included the least number of times were social vulnerability and economic benefits (Figure 1). Social vulnerability can include many factors and the interaction between these can be complex and hard to quantify (Meerow and Newell 2017). The indicators used to quantify social vulnerability were 1) Social Vulnerability Index (SoVI), 2) median household income, and 3) median real estate values (Meerow and Newell 2017; Zucca, Sharifi, and Fabbri 2008).The low rate of inclusion for social vulnerability in these S-MCDA models for green infrastructure ecosystem services exemplifies a gap in the existing literature. It's important to include social vulnerability into such an analysis because lack of access to green space usually disproportionately targets low-income and minority neighborhoods (Meerow and Newell 2017). Therefore, the model developed for this thesis will explore methods to easily quantify and include factors relating to social vulnerability that will be generalizable and replicable.

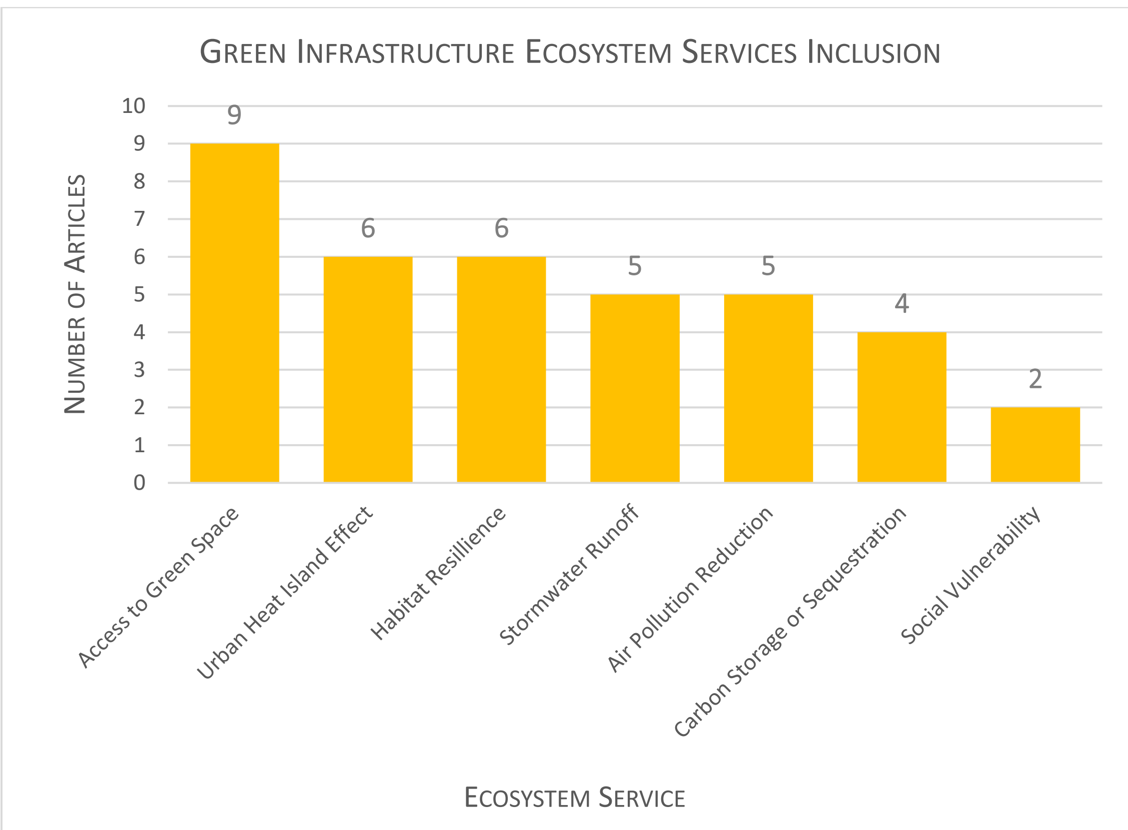

Figure 4: Number of models that included specific green infrastructure ecosystem services.

Land Suitability Factors Inclusion

Inclusion of a land suitability analysis in addition to the S-MCDA of ecosystem services is not prevalent in existing models. Only 3 of the models included some sort of land suitability factor in their analysis (see Table 5). Zucca, Sharifi, and Fabbri (2008) included various sub-factors for protection and restoration of land. For example, they included prioritization of degraded urban areas and areas with new development for the integration of green infrastructure. Giordano and Riedel (2008) included flood plains and permanent preservation areas in their greenway site selection analysis. Lastly, Gül, Gezer, and Kane (2006) included the highest number of land suitability factors (10) when analyzing the most suitable area for a new urban forest. Some of these factors included: undeveloped land, soil properties, slope, protection of areas with historic value, and land ownership.

The addition of a green infrastructure land suitability analysis to the S-MCDA of green infrastructure ecosystem services is another goal for this thesis to add to the existing framework. The land suitability analysis will help provide a more specific analysis of prioritizing green infrastructure locations by focusing on areas that are feasible for development. For example, public versus private ownership of land will determine the feasibility for government agencies to development green infrastructure. Meerow and Newell (2017) emphasize this point by identifying their model as an initial step for spatial multifunctional resilience planning, but not a land use suitability analysis because it does not consider “land use, cost, or other constraints on green infrastructure development”.

Table 4: Ecosystem Services of Green Infrastructure by Source Model

	Ecosystem Service							
Source	**Stormwater Runoff**	**Air Pollution Reduction**	**Urban Heat Island Effect**	**Carbon Storage or Sequestration**	**Habitat Resillience/ Landscape Connectivity**	**Access to Green Space/ Health + Recreation**	**Social Vulnerability**	**Economic Benefits**
Meerow and Newell (2017)								
Kremer, Hamstead, and McPhearson (2016)								
McPhearson, Kremer, and Hamstead (2013)								
Madureira and Andresen (2014)								
Holt et al. (2015)								
Larondelle and Lauf (2016)								
Zucca, Sharifi, and Fabbri (2008)								
Giordano and Riedel (2008)								
Gül, Gezer, and Kane (2006)								

Table 5: Land Suitability Factors by Source Model

Source	Land Cover/ Land Use	Soils	Slope	Flood Plains	Protection	Restoration	Other
	Land Suitability Factors						
Meerow and Newell (2017)							
Kremer, Hamstead, and McPhearson (2016)							
McPhearson, Kremer, and Hamstead (2013)							
Madureira and Andresen (2014)							
Holt et al. (2015)							
Larondelle and Lauf (2016)							
Zucca, Sharifi, and Fabbri (2008)							
Giordano and Riedel (2008)							
Gül, Gezer, and Kane (2006)							

Summary

Based on this analysis of nine S-MCDA models, six main gaps in green infrastructure related S-MCDA models were identified:

1. **Modelling with more than two ecosystem service inputs using a suitability analysis.**
2. Multi-scale analyses to inform better green space planning.
3. **Inclusion of both quantitative and spatial statistics analysis of ecosystem service interactions.**
4. **Inclusion of weighting scenarios.**
5. **Inclusion of social vulnerability as a factor in the analysis.**
6. Inclusion of green infrastructure land suitability analysis.

This thesis aims to address four of the six identified gaps (those which are bolded above). Gap #2 is not addressed in this report but holds potential for further research. Gap #6 was not addressed in terms of physical suitability of green infrastructure. As this thesis defined green infrastructure to be the greater green network in a city, it is not appropriate to specify physical suitability factors such as slope and soil type. Instead, this thesis will look at land use and land ownership to narrow down options for green infrastructure siting.

Existing S-MCDA Models of Green Infrastructure Ecosystem Services: Measuring Ecosystem Services

Overview

The indicators listed in this chapter will be used in my analysis and were chosen based on ecosystem services included in S-MCDA models reviewed. A summary of how each ecosystem service was measured in existing green infrastructure S-MCDA models is discussed which informed how each benefit was measured in this thesis.

Stormwater Runoff Mitigation

Four studies from the literature review in Chapter 3 quantified the potential to mitigate runoff by infiltrating stormwater using green infrastructure. Three of the studies used similar methods using curve numbers from the USDA TR-55 formula. This formula identifies a curve number that describes the proportion of runoff for a given rain event while taking into account land cover type and hydrological soil type (which includes infiltration capacity of the soil) over the course of a determined type of storm.

Kremer, Hamstead, and McPhearson (2016) and McPhearson, Kremer, and Hamstead (2013) used the hydrologic soil groups from the New York City soil survey, landcover dataset for their analysis. Using the TR-55 formula, they calculated inches of runoff during a 24h 5 inch rain event. This resulted in a raster where each pixel was assigned a stormwater absorption coefficient calculated as percent of rain absorbed. The ratio of runoff in inches per inch of precipitation can be calculated by subtracting this absorption coefficient from 1.

Similarly, Holt et al. (2015) used land cover and soils map to assign curve numbers from USDA. For their study, they picked two rainfall event scenarios: one to represent a typical rainfall event, and one that causes extensive flooding. Runoff volume per square meter was assigned to each unique combination of soils and landcover. Holt et al. (2015) compared these results to a scenario where there was no soil and the land cover was all impervious. Volume of runoff reduction due to natural land cover was determined by subtracting the natural land cover runoff scenario from the impervious cover scenario.

Meerow and Newell (2017) did not use the TR-55 and curve number method to calculate runoff, but instead used the Rational Method. This method was a simpler way of calculating a runoff coefficient by Census Tract using land use data. In addition to this indicator, they also used CSO data to calculate the total discharge of untreated sewage for each census tract.

Given access to spatial hydrologic soil group data and land cover data, the TR-55 method to determine curve numbers (and thus runoff) by pixel would be possible for this analysis. The USDA Natural Resources Conservation Service (NRCS) provides this data through their Web Soil Survey (WSS), and online soil data and information resource. However, currently WSS does not have available spatial hydrologic soil group data for the City of Seattle. Instead, flow accumulation was used as a proxy to map areas where stormwater runoff would accumulate.

Air Pollution Mitigation

Three main metrics were used by other studies to measure air pollution or its mitigation: 1) PM 2.5 emissions, 2) removal rate by vegetation, and 3) removal rate using deposition velocity.

1. Meerow and Newell (2017) included air pollution into their model by using particulate matter (PM 2.5) emissions data. Their data originated from a study that simulated the annual average emissions of particulate matter less than 2.5 micrometers and were high-resolution traffic-related air pollution estimates. Meerow and Newell (2017) reasoned to use PM2.5 because WHO concluded that long-term exposure to PM 2.5 has a higher mortality risk than PM20.
2. Kremer, Hamstead, and McPhearson (2016) and McPhearson, Kremer, and Hamstead (2013) incorporated air pollution mitigation into their study by using a metric from an urban forest survey of trees in New York and a survey of pollution removal rates in

Chicago. The survey looked at pollution removal rates of SO2, NO2, PM10, O3, and CO for coarse vegetation, and SO2, NO2 and PM 10 for fine vegetation.

3. Holt et al. (2015) and Larondelle and Lauf (2016) both looked at the removal rate of air pollution (NO2 and PM10) using deposition velocity on different types of land cover. Holt et al calculated estimates of deposition velocity and overlaid this on a land cover map to calculate the average for a 500 meter grid. The total flux of pollution deposition to the land cover of each pixel was calculated from these two layers.

The last two methods focus on rate of removal of air pollution; however, what this analysis should focus on is where the need for air pollution mitigation is located. Meerow and Newell (2017)'s method of using existing air pollution data is the most appropriate for this analysis because it shows current levels of air pollution spatially, where higher concentrations of pollution have the highest need for green infrastructure. The use of this method relies on available air pollution data and the ability to interpolate it across the area of interest. Unfortunately, there is no readily available air pollution data that is large enough for interpolation in the City of Seattle; therefore, road buffers and air pollution emissions from hazardous sites were used as a proxy to identify high priority air pollution mitigation areas.

Carbon Sequestration

Carbon sequestration was one of the metrics used in some studies (Kremer, Hamstead, and McPhearson 2016; McPhearson, Kremer, and Hamstead 2013; Larondelle and Lauf 2016). Kremer, Hamstead, and McPhearson (2016) and McPhearson, Kremer, and Hamstead (2013) both used carbon sequestration rates for coarse and fine vegetation from another study. Larondelle and Lauf (2016) found both the annual CO2 sequestration with the growth of trees and compared this to the demand for sequestration based on produced carbon emissions by different sources (eg. households, traffic). On the other hand, Holt et al. (2015) used a carbon storage model that assesses the capacity for, and spatial pattern of, carbon storage. Their approach used land cover based estimates of carbon biomass in different types of vegetation.

For the purposes of this study in determining areas of need for carbon sequestration, both carbon sequestration rates and carbon emissions are possible metrics, depending on availability of data. Determining carbon sequestration rates of vegetation, where areas of low carbon sequestration are those in need of green infrastructure is a simpler approach than calculating CO2 emissions. Another study that has been referenced by several of the reviewed articles provided a simple equation where carbon sequestration can be derived from tree canopy cover data. Whitford, Ennos, and Handley (2001) used a method that only required spatial data of percent tree canopy cover; this data was inputted into Equation 1 to calculate carbon sequestration in tons per acre. As percent tree cover data can be downloaded for free from the National Land Cover Dataset, this approach, being the simplest and most straightforward, was used for this analysis.

Equation 1: Carbon storage (tonnes ha^{-1}) = 1.063 x % tree cover

Urban Heat Island Effect Mitigation

Most of the studies discussed in Chapter 3 measured the urban heat island effect using the proxy of land surface temperature (Meerow and Newell 2017; Kremer, Hamstead, and McPhearson 2016; Madureira and Andresen 2014; Holt et al. 2015). However, the metric for land surface temperature varied across studies. Meerow and Newell (2017) used average daytime surface temperature per census tract derived from the Moderate Resolution Imaging Spectrometer (MODIS) sensor, while Kremer, Hamstead, and McPhearson (2016) Kremer and

Madureira and Andresen (2014) used land surface temperature from Landsat data. Holt et al. (2015) used a model from another study that estimates maximum daytime surface temperature.

As Landsat satellite imagery data, is free and readily available online, deriving land surface temperature using remote sensing technologies will be feasible for this analysis.

Habitat Connectivity and Buffers

Patch cohesion and structural connectivity of the landscape were included in several studies (Meerow and Newell 2017; McPhearson, Kremer, and Hamstead 2013; Holt et al. 2015; Zucca, Sharifi, and Fabbri 2008; Giordano and Riedel 2008). Two main methods for determining areas prime for connectivity were used: 1) measure physical connectedness of habitat patches, and 2) proximity to green areas.

1. Fragstats, an open source software, was used to measure physical connectedness of habitat patches (Meerow and Newell 2017; Holt et al. 2015; Giordano and Riedel 2008). This software produced a patch cohesion score for each spatial unit indicating suitability for creation of a habitat corridor.
2. McPhearson, Kremer, and Hamstead (2013) took a different route and instead looked at proximity to green areas. They used the Near tool in ArcGIS to search a 500 meter buffer around existing green spaces to determine how close green areas are to each other in the city. Those that are close together are given higher ranking to be connected by habitat corridors.

After researching Fragstats and other corridor and connectivity mapping models, it is evident that there is no easy way to create a strong connectivity analysis without professional and expert input on what species to base the model on.

Other than lack of interaction with a larger pool of wildlife, another negative consequence of habitat fragmentation is wildlife exposure to the edge effect and human development. One way to mitigate this exposure is through habitat buffers. As this is a much simpler approach to including wildlife resilience in the model, habitat buffers was included in the analysis rather than habitat connectivity.

Access to Green Space

Studies that included access to green space in their models measured it either by population density, proximity, or both. Meerow and Newell (2017) calculated the percent of population without park access for each Census Tract. They determined that residents outside of a ½ mile buffer from green spaces do not have sufficient access to green space. Kremer et al 2016 looked at mean population density as an indicator for level of potential use of specific parks by people living in close proximity. Access to a park was defined as within 500 meters.

McPhearson, Kremer, and Hamstead (2013) determined in their study that a low population density means there is low social need for access to green space, but also that an area with low green space available has a high need for access to green space. Similar to Kremer, Hamstead, and McPhearson (2016), McPhearson, Kremer, and Hamstead (2013) used a 500 meter distance from parks as the cut off for access to green space.

Unlike the last three studies, Madureira and Andresen (2013) brought in a more detailed analysis for access to green space by including different weights for different types of greenery. They looked at proximity to public gardens and parks, semi-public gardens or tree lined public squares, and street trees or green alleys. Larger green spaces were given higher weight for access to green spaces.

This analysis applies methods from the first three studies by measuring access to green space using both population density and distance from existing parks. Good spatial data available for smaller types of green spaces such as street trees or green alleys is not available, therefore, different weighting for various greenery will not be used. Instead access to green space will be ranked based on a walking distance from a park access point.

Social Vulnerability

Only two studies included some type of social vulnerability measure in their models (Meerow and Newell 2017; McPhearson, Kremer, and Hamstead 2013). Meerow and Newell (2017) used a Social Vulnerability Index (SoVI) created by the Hazards and Vulnerability Research Institute at the University of South Carolina. This data is freely available online and is widely-used. The SoVI 2006-2010 score consists of a composite of 30 socio-economic and demographic variables such as wealth, age, housing, and race.

McPhearson, Kremer, and Hamstead (2013) looked at the need for green infrastructure ecosystem services near vacant lots. They looked at medium household income and median real estate values within 500 meters of vacant lots. A low household income with low real estate value was classified as having a high social need for green infrastructure benefits.

Since SoVI is freely available, widely-used, and includes 30 different socio-economic variables, this dataset was used for the analysis to measure social vulnerability.

Summary

After analyzing 9 S-MCDA models on green infrastructure ecosystem services, I will be including 8 ecosystem services in my analysis. The quantification of each ecosystem service for this analysis is built on how these 9 S-MCDA models have measured them, how simple the methodology is, and data availability. The next chapter provides a more detailed explanation of my methodology.

Chapter 5 // Methodology

Overview

The goal of this analysis is to identify areas that have a high need for green infrastructure across many ecosystem services. This analysis includes 4 sections (Appendix A, Figure 26). The first looks at mapping areas of need for green infrastructure ecosystem services. The second section briefly describes how social vulnerability is mapped and included in this analysis. Third, final raster layers from the previous two sections are combined in several weighted scenarios whose output will illustrate areas of high need for green infrastructure that addresses several benefits. Finally, spatial statistics will be performed on the raster layers from the first two sections to get a better idea of how many parcels by public/private ownership and land use have a high to medium-high need for green infrastructure benefits.

Raster Settings and Projection

Each raster surface was pre-processed to rank areas low to high, on a scale of 1 (low) to 5 (high), based on their need for that specific ecosystem service (Appendix A, Table 8). This resulted in a raster layer for each ecosystem service that will be used for a weighted scenario overlay analysis and spatial statistics analysis. All rasters are processed at a 30 x 30 ft scale. This cell size was selected based on the elevation dataset used which was close to 30 x 30 ft and was the first raster dataset used in this analysis. It is not too large that details are lost in the analysis, and not too small that processing time was unreasonable. All layers were projected to NAD 1983 HARN StatePlane Washington North (Feet), the projection used by the City of Seattle and King County.

1. Mapping areas of need for green infrastructure

Ecosystem Services

Stormwater Runoff Mitigation (Flow Accumulation)

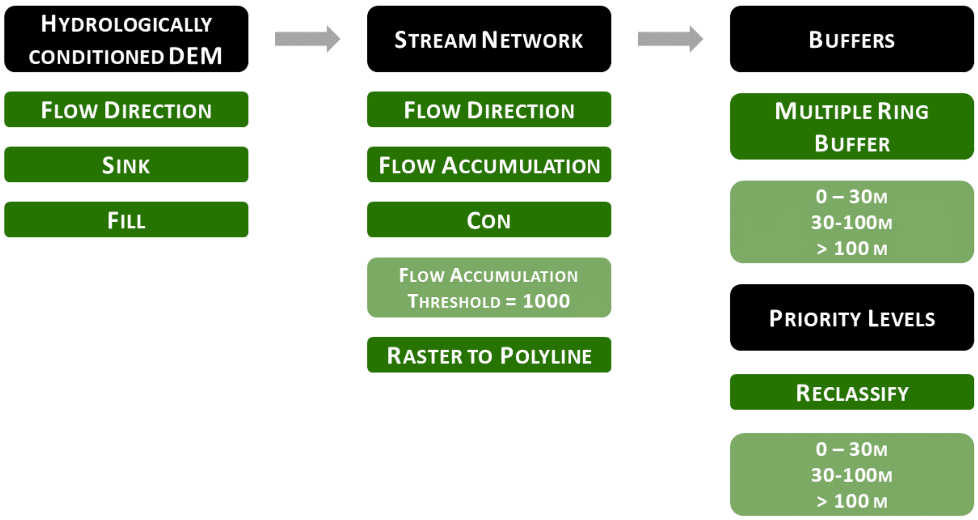

Figure 5: Process workflow for deriving flow accumulation prioritized layer.

As a proxy to map areas of stormwater runoff, a flow accumulation raster was created using an elevation dataset (10m x 10m) from USGS National Elevation Dataset (NED). Figure 5 shows the workflow of creating a flow accumulation layer as derived from the ArcGIS spatial analyst toolbox for deriving runoff characteristics. The resulting raster layer values for each cell indicates how many cells flow into that cell. Instead of using the number of cells as the measure to indicate high to low need of green infrastructure, I decided to use distance from streams of flow accumulation. This is because when resampling the raster from 10m (about 32 feet) to 30 feet, some detail was lost that affected how areas would be ranked by need.

To create buffers around streams of high flow accumulation, I used the Raster to Polyline tool to create line shapefiles for cells with a flow accumulation of greater than 1000 cells (Figure 6). This threshold was chosen as the break point because it includes the major streams of flow accumulation in the map. A brief literature review was conducted to justify the buffer distances from the derived flow accumulation streams. Therefore, the impact of buffer zones on surface pollutants was researched to determine how wide of a buffer is deemed as effectively removing pollutants from the water.

A way to reduce pollutant transport to waterways through runoff is by planting vegetated buffers around the stream of interest (Hickey and Doran 2004). The infiltration within a buffer zone reduces the speed of runoff, allowing for infiltration, and reduction of surface runoff. Infiltration and loss of surface flow velocity encourages pollutant particles to be deposited and filtered out of the water by vegetation and soil (Muscutt et al. 1993). One study (Peterjohn and Correll 1984) found that Nitrogen and Phosphorous reduced by 83% and 81%, respectively when runoff filtered through a buffer. They found that a major portion of pollutants were removed in the first 19 meters. In Muscutt et al. (1993)'s review of buffer zone design and dimensions, they found that effective buffers ranged from 15 to 80 meters wide. Another review by Sweeney and Newbold (2014) that looks at nitrate removal and sediment trapping found that 30 meter buffers are effective in trapping 85% of sediments. Lastly, another review concluded that wide buffers (30-100m) provide waterways with the most effective protection from non-point source pollution (Hickey and Doran 2004).

Based on these reviews, I used the multiple ring buffer tool to create three buffers around the flow accumulation streams: 0 to 30m, 30 to 100m, and greater than 100m. These buffers were then converted to a raster of 30 x 30 ft cells, and reclassified so that the closest buffer was ranked as high need (5) and the lowest was ranked as low need (1) of green infrastructure.

Figure 6: Streams of accumulated flow greater than 1000 cells.

Air Pollution Mitigation (Road and TRI)

One of the more common interpolation methods for air pollution is kriging (Jerrett et al. 2004). Another technique is inverse distance weighting (IDW) which is a more simplified version of kriging as it does not take into account spatial autocorrelation (Jerrett et al 2005). An initial exploration of the data revealed that interpolating air pollution data across the city using kriging or IDW would not be suitable with the toxic release inventory (TRI) air pollution data for 3 main reasons: 1) the sample size is too small (n = 39), 2) the data was not normal, which is an assumption for such interpolation techniques, and 3) there was difficulty fitting the model variogram to the data. These are issues which Jerrett et al. (2004) observed in his review of air pollution studies. Wong, Yuan, and Perlin (2004) in his comparison of IDW and kriging also found that when model variograms could not fit the data, simple kriging methods were not appropriate. They emphasize that there must be justification for application of kriging and IDW for interpolation must show as forcing data into models will create parameter errors (Wong, Yuan, and Perlin 2004). Therefore, rather than allow for large errors in an interpolated air pollution raster, proxies for air pollution mitigation were used for analysis. The two proxies used to identify areas of need for air pollution mitigation are road buffers and toxic release inventory air pollution site buffers.

Road Buffers

Road buffers are a common proxy to gauge air pollution exposure. Studies show that 400m is sufficient for the majority of air pollutants to reach background concentrations (Karner, Eisinger, and Niemeier 2010). Several studies mentioned distances of 150 – 200m as a reasonable distance at which air pollution particles decreased to normal levels. Additionally, it has been observed that air pollution particles experience exponential decay a distance from road increases (Karner, Eisinger, and

Niemeier 2010; Zhu et al. 2002). Based on this information, the following 5 buffer distances were created around major roads (numbers in parentheses correspond to rank of green infrastructure need): 0-50m (5), 50 – 150m (4), 150 – 250m (3), 150 – 400m (2), > 400m (1). The buffers were converted to a raster and reclassified base on the rank of GI need.

TRI Air Pollution Site Buffers

The TRI data was downloaded from the EPA through the TRI explorer. This provided all air pollution totals for each TRI site in pounds emitted. The data was geocoded using XY data and a kernel density was performed to create air pollution density buffers around each facility. Kernel density also allowed to weight some facilities more than others; in this case the weight was pounds of emitted air pollution. A search radius of ½ mile was set based on the buffer Maantay (2007) assigned to the spread of air pollution from TRI facilities. Finally, the kernel density output was reclassified based on quantiles from 1 (low need for air pollution mitigation) to 5 (high need for air pollution mitigation).

Carbon Sequestration

Need for carbon sequestration was derived by calculating existing carbon sequestration rates from percent tree cover. A simple equation from Whitford, Ennos, and Handley (2001) was used and only required percent tree cover data. However, it must be noted that this equation only calculates carbon sequestration of urban trees and does not include other types of vegetation. Whitford, Ennos, and Handley (2001) adopted the equation (below) from Rowntree and Nowak (1991) who provided a method to estimate the carbon sequestered annually per unit area of tree crown (Equation 1).

Equation 1: Carbon storage (tonnes ha^{-1}) = 1.063 x % tree cover

The original equation results in a value that is tons of carbon sequestered per acre. For the purposes of this analysis which is in feet, I modified the equation to be in tons of carbon sequestered per square feet and multiplied this by 900 sq ft to get carbon sequestration by tons per cell in the map (Equation 2).

Equation 2: $$0.00335\ x\ \frac{\%\ tree\ cover}{43560}\ x\ 900\ sq\ ft = carbon\ sequestration\ (\frac{tons}{cell})$$

$Field\ calculator\ equation$: ***0.00335 * [VALUE] / 43560 * 900; VALUE is the percent tree canopy cover.***

I downloaded the National Land Cover Dataset (NLCD) 2011 USFS Tree Canopy analytical raster dataset for the percent tree canopy cover input. The pixel values indicating percent tree canopy cover range from 0 to 100 percent, which represents the percent of that cell that is covered by tree canopy. The original cell size of 30x30m was resampled to 30x30ft. To calculate carbon sequestration, a new field was added to the attribute table and field calculator was used to input the equation above. Natural breaks with 5 classes was used to classify the resulting carbon sequestration field. This attribute was then reclassified 1 to 5 with 1 being the areas with the highest carbon sequestration rates (and least need for green infrastructure benefit).

Urban Heat Island Effect Mitigation

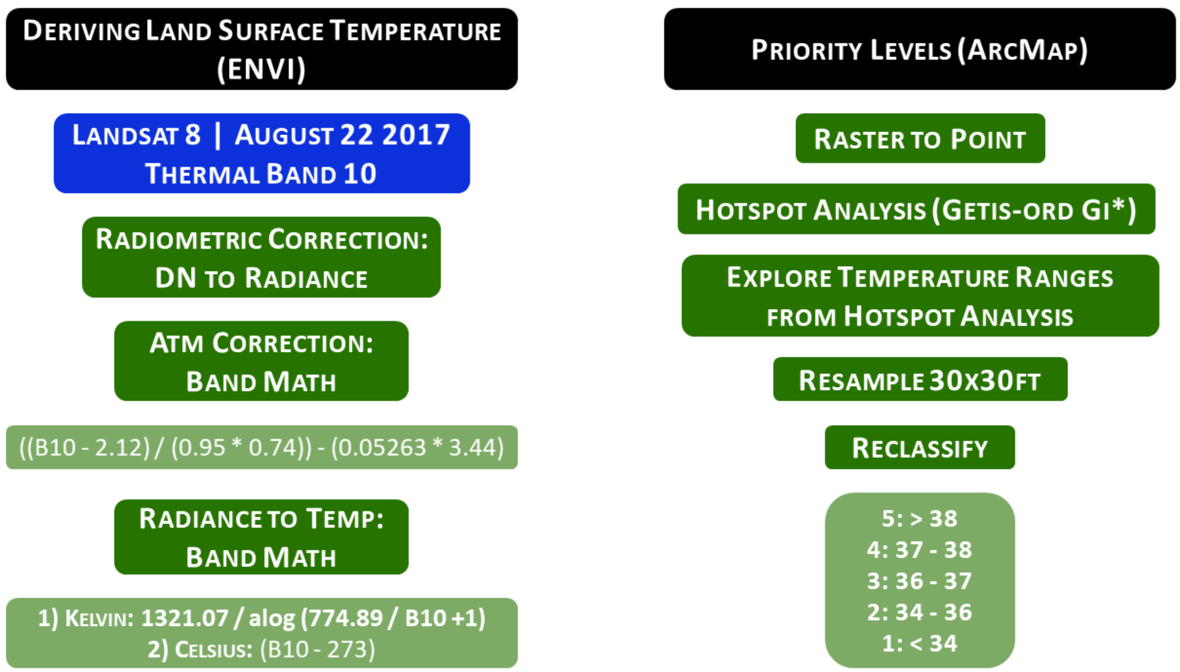

Figure 7: Workflow process for deriving priority levels of need for UHI mitigation.

The City of Seattle's open data portal has road weather information station data which provides averaged ambient air temperature readings per second. Unfortunately, this data is only available for 9 points which is too small of a sample size to interpolate ambient air temperature for the whole city. Instead I used remote sensing tools in ENVI software to derive land surface temperature from satellite imagery (Figure 7). From USGS Earth Explorer, I used a cloudless Landsat 8 OLI/TIRS image (30 x 30m) from 22 August 2017 for this analysis.

The thermal band (Band 10) from this image was radiometrically corrected from digital numbers (DN) to radiance. An atmospheric correction calculator from NASA was used to perform atmospheric correction on the radiance values. I then use Band Math to convert radiance to temperature in Celsius and import the resulting raster into ArcMap. To determine how to classify the land surface temperature into 5 classes I used the Hotspot Analysis Tool

(Getis-Ord Gi*) to identify localized UHI effect. This tool returns a z-score that indicates more intense clustering of high values the larger it is, and clustering to low values the smaller it is. The result is Figure 8 showing areas of statistically significant hot spots in temperature. However, comparing this to a stretched image of the original temperature map shows that it is missing some details within the highest hotspot ranking. To tease this detail out, I ran the hotspot analysis tool again but just on the areas with 99% statistically significant hot spots from the first analysis. From these two hot spot analyses, I used the cut off points for significance to inform classification of the original land surface temperature map (Table 6). I resampled the data down to 30x30ft and reclassified the classes from 1 to 5, where 5 indicates the highest land surface temperature and in need of green infrastructure for UHI mitigation.

Table 6: Priority levels for UHI mitigation need based on hot spot analysis results

Hot Spot Analysis (Confidence)					
First	**Second**	Min (Celsius)	Max (Celsius)	Classification	Reclassify
Cold (90 to 99%)	N/A	19.9854	36.9612	19.9854 – 34	1
Not Significant, Hot (90 to 95%)	N/A	28.525801	39.680302	34 – 36	2
Hot (99%)	Cold (95 to 99%)	34.997799	45.990898	36 – 37	3
Hot (99%)	Cold (90%), Not Significant	34.751499	43.25	37 – 38	4
Hot (99%)	Hot (90 to 99%)	32.599098	49.529598	38 – 49.529598	5

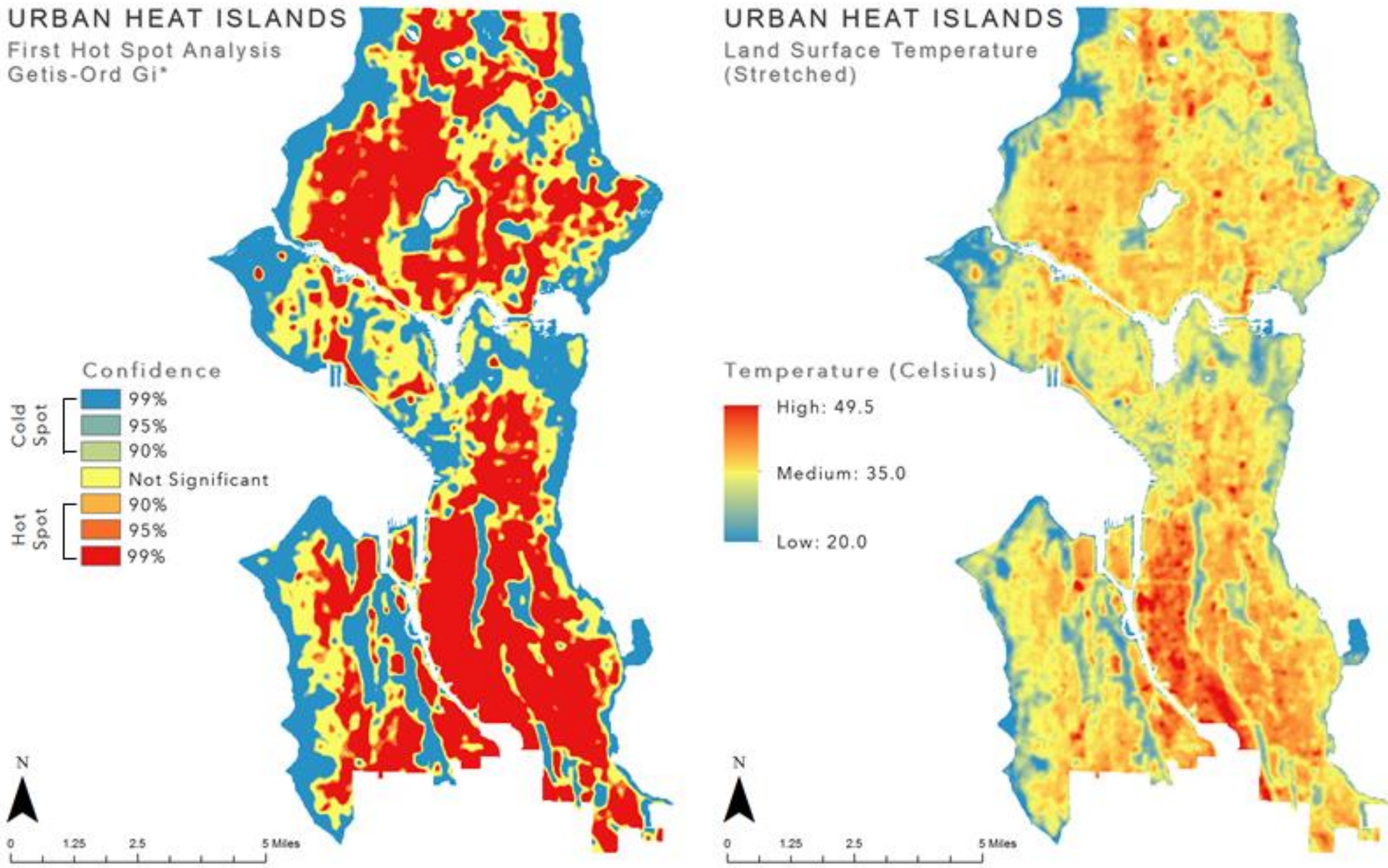

Figure 8: Left - first hot spot analysis results showing significant hot spots. Right - land surface temperature using a stretched symbology.

Habitat Buffers

As discussed in Chapter 3, existing S-MCDA models on GI benefits include areas for habitat connectivity and patch cohesion as areas of high need for GI. However, after researching Fragstats and other corridor and connectivity mapping models, it is evident that there is no easy way to create a strong connectivity analysis without professional and expert input on what species to base the model on. Therefore, a simpler approach was used for my model; I decided to focus on habitat buffers around environmentally critical area which will also provide benefits to mitigating edge effects of habitat patches.

Between high corridor connectivity and large patch size, the latter is more important in encouraging biodiversity (Whitford, Ennos, and Handley 2001). Patches of habitat indicate high fragmentation which increases the edge areas of a patch. This edge effect exposes biodiversity to human environments and can lead to negative impact on wildlife (Whitford, Ennos, and Handley 2001). One way to mitigate habitat fragmentation is connectivity between patches, however, since I already established this is not possible in this analysis, buffer zones is another way to create viable habitat around wildlife areas and reduce the exposure of biodiversity to the edge effect (The Nature Conservancy 2013).

For this analysis, I determined what buffer width is effective in reducing exposure to edge effects. TNC recommends a buffer of at least 330 ft around streams. However, they also suggest that to support a variety of wildlife, a buffer of 1,300 ft would be ideal. According to the City of Seattle's Environmentally Critical Areas code, a riparian corridor must have a buffer of 75ft, and wetlands should have a buffer of 50 – 200 ft. From this research, the minimum buffer should be around 300ft while the maximum should be around 1,300ft. Therefore, for my habitat buffer widths I decided to use the following: 0 – 300ft (5), 300 – 600ft (4), 600 – 900ft (3), 900 – 1300 ft (2), and > 1300ft (1).

The City of Seattle has a shapefile with areas considered Environmentally Critical Areas. I used areas categorized as wildlife, wetlands, and riparian corridor for this analysis. After running the multiring buffer tool, I converted the output to a raster and reclassified it according to the ranking specified above.

Access to Green Space

Before conducting a walkshed around existing green spaces in Seattle, I determined what a walkable distance is for a park. Studies have identified a walkable distance to be about a ½ mile (about a 10-minute walk) from park entry points along a walkable street network (Meerow and Newell 2017; McPhearson, Kremer, and Hamstead 2013). However, Seattle has a standard where residents in an urban village should have access to a park within 1/8 mile. Urban villages consist of 30% of the city, while the other 70% has a standard of a ½ mile distance from parks. Therefore, I based my walkshed buffers on Seattle's standards.

Based on Seattle's street centerline data, I created a walkable street network that removes highways and street ramps. Park access point data was received from the Parks and Recreation department. Using this data, network analysis was used to create 1/8 mile and ½ mile walksheds for all park access points. I used the intersect tool on the 1/8 mile walkshed and the urban village boundary to create a shapefile with access to green space within urban villages only. To select out a layer with a ½ mile walkshed outside of the urban villages boundary I used the union tool and selection. Finally, I merged the 1/8 mile walkshed inside urban villages and ½ mile walkshed everywhere else to create a final walkshed boundary. This shapefile was converted to a raster and reclassified so that the walkshed is given a value of 0 while every cell outside is given a value of 5 (Figure 9).

Having a walkshed does not consider demand based on number of people or population density. Where there is a higher population density, the need for access to green space should be ranked higher. Using ACS 2012 – 2016 5-year estimates for population density, I created a raster where classes were based on quantiles. This was reclassified so that the least dense areas are classified as 1 and the densest areas are classified as 5.

To combine the walkshed raster and population density raster, I multiplied them using raster calculator. Since walkshed areas were classified as 0, any cells regardless of population are given a value of 0, which was later reclassified to 1 (low need for GI). The remaining values created are 5, 10, 15, 20, and 25. The value 5 represents areas outside of the walkshed (5), but have low population density (1), therefore this will be reclassified to 1 as a low population density indicates less need for access to green

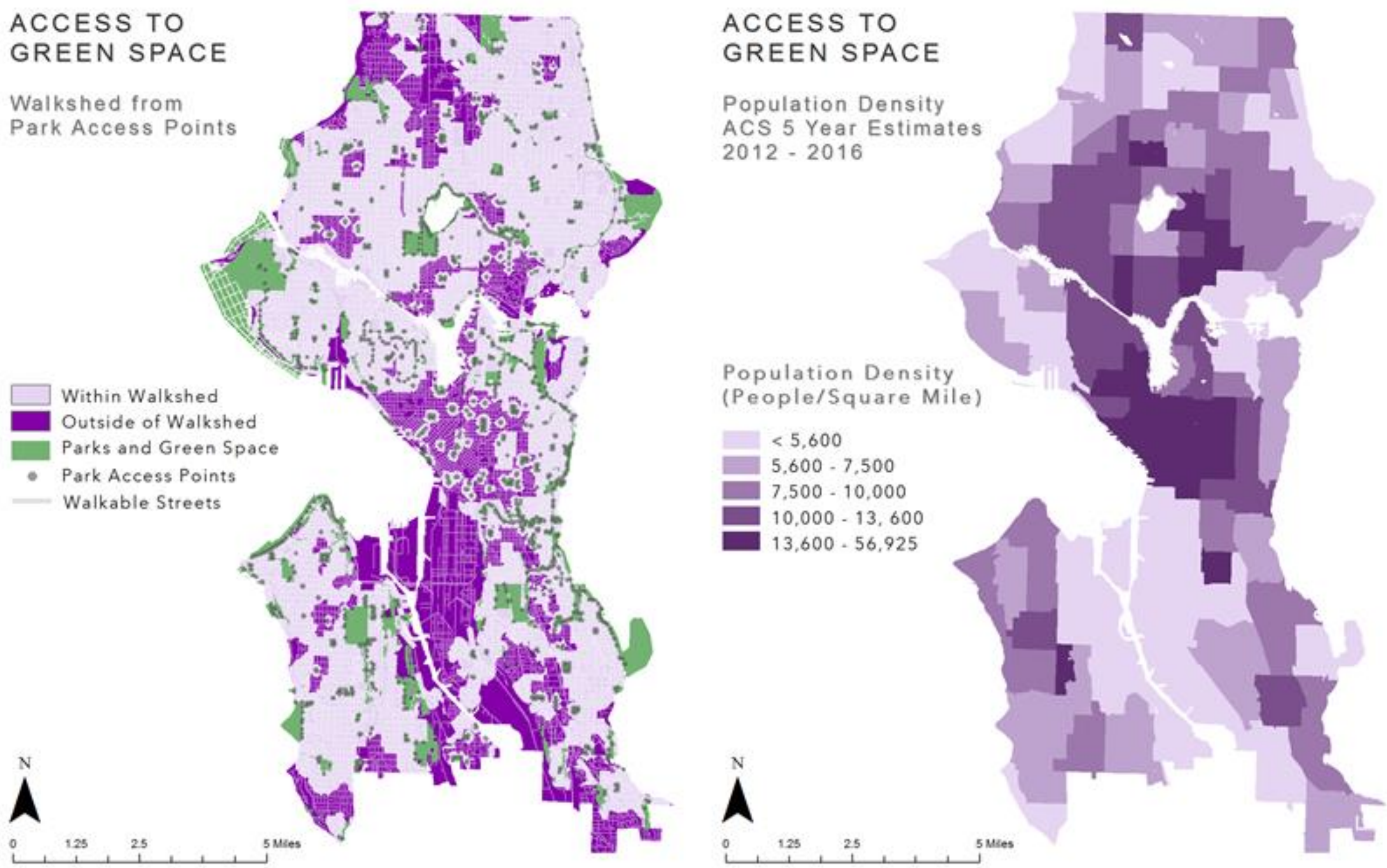

Figure 9: Left - walkshed map showing which areas are within walking distance to park access points. Right - population density map of Seattle based on ACS 5-year estimates (2012-2016).

Table 7: Access to green space reclassification values.

Walkshed Category	Population Density Category	Walkshed Class	Population Density Class	Final Value	Reclassify
Within	< 5,600	0	1	0	1
Within	5, 600 – 7, 500	0	2	0	1
Within	7,500 – 10,000	0	3	0	1
Within	10,000 – 13,600	0	4	0	1
Within	13,600 – 56,925	0	5	0	1
Outside	< 5,600	5	1	5	1
Outside	5, 600 – 7, 500	5	2	10	2
Outside	7,500 – 10,000	5	3	15	3
Outside	10,000 – 13,600	5	4	20	4
Outside	13,600 – 56,925	5	5	25	5

2. Social Vulnerability Mapping

To map social vulnerability, I used the Social Vulnerability Index (SoVI) created by the Hazards and Vulnerability Research Institute at the University of South Carolina which was funded by the NOAA Office of Coastal Management (NOAA n.d.). This dataset is freely available, well-established, and widely-used for similar analyses (Meerow and Newell 2017). The index compiles 30 socioeconomic variables from the American Community Survey 2006-2010 to create a metric that examines the social vulnerability to environmental hazards. The data is only available at the Census Tract level.

Statistical analysis on the 30 variables included in SoVI was conducted by the Hazards and Vulnerability Research Institute. It was found that 7 of the 30 variables explain 72% of the variance in the data (Hazards & Vulnerability Research Institute n.d.). These variables include race and class, wealth, age, Hispanic ethnicity, Native American ethnicity, elderly residents, and employment in service industries (University of South Carolina n.d.).

When visualizing the data spatially, SoVI is represented in quantiles with the following classification: high (top 20%), medium high, medium, medium low, and low (bottom 20%). More vulnerable census tracts are those classified as high, and least vulnerability are classified as low. The classification into quantiles was helpful as I only had to convert the data to raster and reclassify high to low classes to 5 to 1, respectively.

3. Weighted Scenario Overlay

Once each GI ecosystem service and the social vulnerability layer have been reclassified on a 1 to 5 scale (5 indicating the highest need for that specific benefit or high social vulnerability), several weighted scenarios were created as part of a basic sensitivity analysis. A tool was created in ModelBuilder (Appendix A, Figure 27) to automate creation of the 9 different scenarios listed in Appendix A, Table 9) through batch processing. The first scenario provides equal weighting of all the layers, while subsequent scenarios weight one layer three times higher than the others. Resulting areas with the highest raster score indicate a need of more than one ecosystem service provided by green infrastructure. These are the areas that should be prioritized for green infrastructure siting. By weighting one benefit over the others in each scenario, the result will illustrate how areas of need for GI change when emphasis is put on one type of benefit over another. These scenarios were descriptively compared and are discussed in the results section.

4. Spatial Statistics

Statistical tools were used to answer questions about how locations were prioritized by land use and ownership, area of high and medium-high priority agreement in acres, and synergies and tradeoffs between ecosystem services.

Summary Statistics: Individual Ecosystem Benefits

How many parcels by ownership (private vs public) and land use have a high to medium-high need?

I analyzed the resulting ecosystem benefit rasters to determine the number and area of parcels ranked high to low need for GI. Parcel data was downloaded from the King County open data portal and clipped down to Seattle's boundary; however, this shapefile did not have public and private ownership information. Another shapefile of only public parcel ownership was used to select public parcels in the all parcels data. A new field was created, and selected parcels were classified as "Public", while all other parcels were classified as "Private". The parcel data included land use data which I used to create a new field with broader land use classifications including residential, open space and recreation, transportation, commercial, industrial, institutional and public buildings and other.

Zonal statistics was used on the processed parcel data and individual ecosystem benefit rasters to get a majority GI need rank value for each parcel. The frequency tool was used to produce a table summarizing number of parcels by ownership and land use for each ecosystem benefit which was also broken down by ranking of GI need.

Summary Statistic: Areas of Agreement Between Ecosystem Benefits

How many ecosystem benefits are ranked high or medium high need for GI in the same parcel?

The weighted scenarios show areas of high need for GI, but it does not distinguish how many of those benefits are ranked high or low in a specific area. Therefore, I identified areas of agreement for high (5) to high-medium (4) need between ecosystem services. To calculate the number of occurrences of high (5) or high-medium (4) need across the ecosystem services, I used a Local tool called Greater than Frequency in ArcGIS. This tool determines for each cell how many times the rank "5" or "4" occurs from the ecosystem services rasters. If a cell is given a value of 3, that means 3 ecosystem services were given a rank of "5" or "4". If GI is sited at that location, three ecosystem services with a high or medium-high need for GI will be addressed.

The resulting raster was combined with the parcel data in the zonal statistics tool to get a majority occurrence for each parcel. The frequency tool was used to produce a table summarizing number of parcels by ownership and land use.

Spatial Correlation: Synergies and Tradeoffs

Are there any pairs of ecosystem benefits that have a positive relationship (both have high need for GI or both have low need for GI) or a negative relationship (one has a high need while one has a low need)?

To investigate tradeoffs and synergies between ecosystem services I conducted spatial correlation. The first tool used was Band Collection Statistics in ArcGIS, which produced a table with correlation statistics for each ecosystem benefit pair giving an idea of whether there are any existing correlations.

Based on the results from Band Collection Statistics, to investigate correlations at a spatial level, I used Geoda to analyze pairs of ecosystem services that had a relatively strong negative or positive correlation using Bivariate Local Moran's I. A bivariate spatial correlation analyzes the correlation between one variable and the spatial lag of another. Spatial lag is the average of the neighboring values of a location. Therefore, a bivariate spatial correlation "measures the degree to which the value for a given variable at a location is correlated with its neighbors for a different variable" (GeoDa n.d.). When deciding which variable to compare to the spatial lag of another, it is important to remember that spatial correlation investigates how neighbors affect a central location (GeoDa n.d.).

The Bivariate Local Moran's I in Geoda gives three 3 products:

1. Significance Map: This map shows areas with a significant local statistic at different p-value levels (0.05, 0.01, and 0.001). It shows where the relationship between one variable and the spatial lag of another variable is significant.
2. Cluster Map: This map shows 4 cluster classifications – 1) High-high, 2) low-low, 3) low-high, and 4) high-low. These clusters represent areas of correlation between high (or low) values of one variable and high (or low) neighboring values of another variable. The linking feature between the significance and cluster map in Geoda makes it easy to compare which areas are more significantly related that others. If Band Collection Statistics results indicate a negative correlation between two variables, we expect to see more Low-High or High-Low areas in the Cluster Map. If Band Collection Statistics indicate a positive correlation between two variables, we expect to see more High-High or Low-Low areas in the Cluster Map.

3. Bivariate Moran's I Scatterplot: The scatterplot shows one variable on the x-axis and the spatial lag of another variable on the y-axis. The scatterplot has 4 quadrants which represent the 4 classifications in the cluster map. It also gives a Moran's I statistic which falls between -1.0 and +1.0. A positive Moran's I statistic indicates a high-high or low-low cluster relationship; a negative Moran's I statistic indicates a high-low or low-high cluster relationship.

SUMMARY

The outputs from this model include:

1. Individual ecosystem services maps depicting priority need levels for each benefit.
2. Maps depicting multi-benefit priority areas in differently weighted scenarios.
3. Land use and ownership statistics for individual ecosystem services maps.
4. Land use and ownership statistics for the areas of ecosystem services agreement map.
5. Spatial correlation between pairs of ecosystem services to identify any synergies and tradeoffs.

The next chapter will analyze these outputs and discuss what they mean for green infrastructure planning in Seattle, Washington.

Chapter 6 // Results

Overview

The results from the S-MCDA model are all rasters. To give a better idea of how much public land is available for development and the type of land use, I provide a breakdown of parcels by public and private ownership and land use by priority. There are three sections to this chapter: 1) summary statistics of individual ecosystem services, 2) an analysis of equally weighted interactions between ecosystem services, 3) comparison of weighted scenarios, and 4) statistical analysis of synergies and tradeoffs.

1. Summary Statistics: Individual Ecosystem Services

For each individual ecosystem service map, the location of high priority level is discussed as well as any limitations or sources of error that would influence these results. Additionally, the priority level that is assigned the most land area is identified. The opportunity for development of green infrastructure on publicly owned land for high priority areas is explored, as well as the priority level for most of the public land. A comparison is made between the ratio of public versus private land for high priority areas. Finally, the top two land uses for high priority areas are identified.

Priority levels for each parcel was assigned based on the majority rank of all the cells within that specific parcel. This allowed for identification of land ownership and land use of different priority levels; however, it also brought in potential errors. For example, not all parcels are the same size and large parcels are only given one priority level. At a finer scale there may only be specific locations within that parcel that needs flow accumulation mitigation through green infrastructure or other ecosystem services. Despite these limitations, having acreage of high priority land is useful for City planners to understand how much land is available for development of multifunctional GI projects.

Flow Accumulation Mitigation

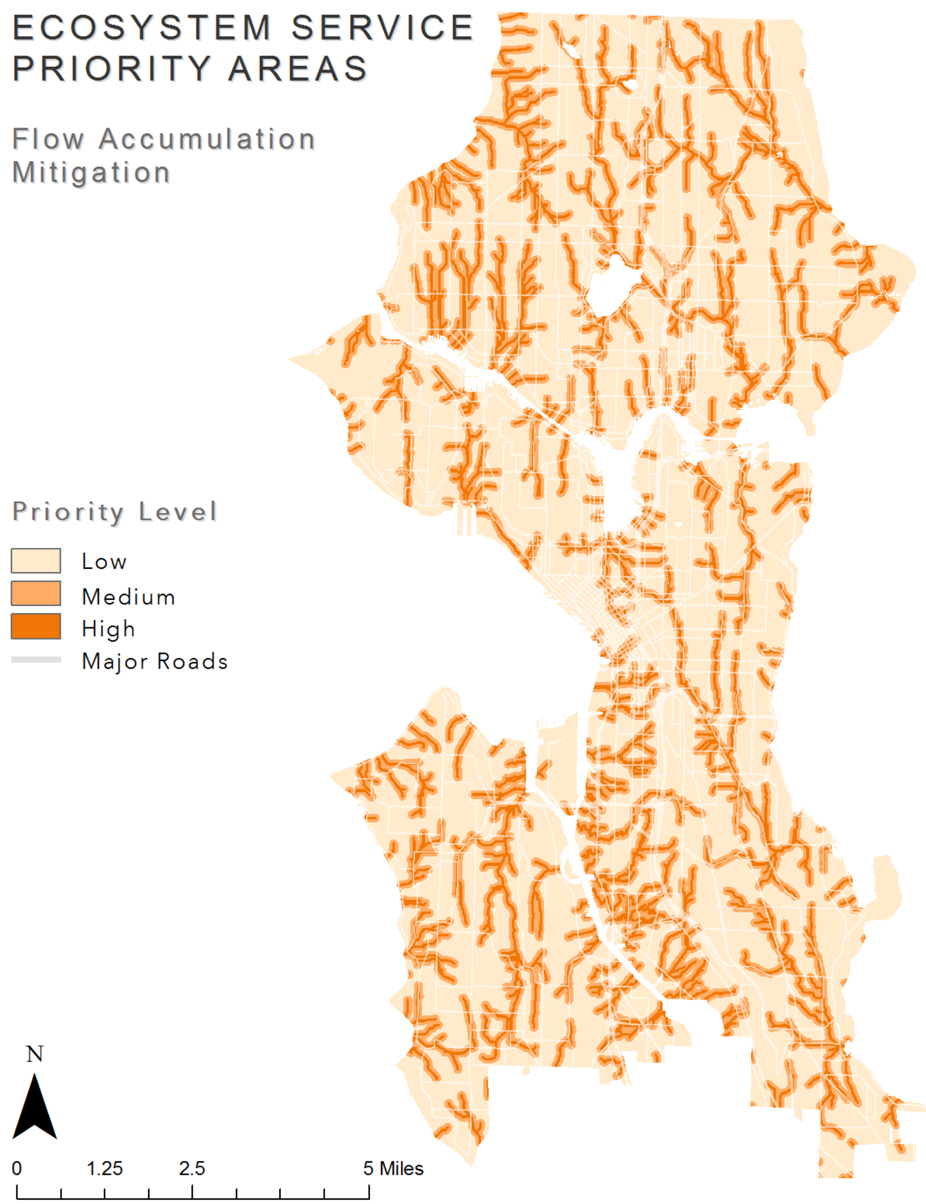

Figure 10: Priority level for flow accumulation mitigation need.

High Priority Locations

Highest priority areas for flow accumulation mitigation are spread out across the city where elevation is lower than the surroundings. These areas most likely experience high volumes of stormwater runoff if there is not much infiltration from the surrounding area draining into the flow accumulation streams. However, the result is a highly simplistic proxy for what the actual conditions of stormwater runoff are as it does not consider soil type and infiltration. Additionally, it does not include a scenario estimate using a specific rain event to provide runoff and infiltration volumes. For the purposes of this analysis it provides a general guideline for where there could be a need for green infrastructure. As the USDA NRCS is currently mapping the soil hydrological groups of the city of Seattle, once the data is available it would be interesting if future research used that to create a layer that represents actual priority areas for stormwater runoff mitigation.

Public vs Private Ownership

Although the ownership of land in high priority areas is mainly privately owned, about 10% of the land classified as high priority is on public land, and about 20% of the area classified as medium priority is on public land. This offers the City of Seattle an opportunity to analyze these specific areas for stormwater management. Overall, most of the total land area has a low priority level which makes sense because there is a focus only on specific streams of accumulated runoff which may not have a large surface area. However, any kind of green infrastructure across the city, whether it is close to or far away from an identified runoff stream, will help to reduce the total runoff in general.

Land Use

The top two land uses for high priority areas are residential and commercial. As most of the land in the City of Seattle is residential, in order to achieve stormwater runoff goals through the use of GI, there needs to be programs to encourage residents to adopt strategies that allow stormwater runoff to infiltrate the soil (eg. educational outreach programs).

Air Pollution Mitigation from Major Roads

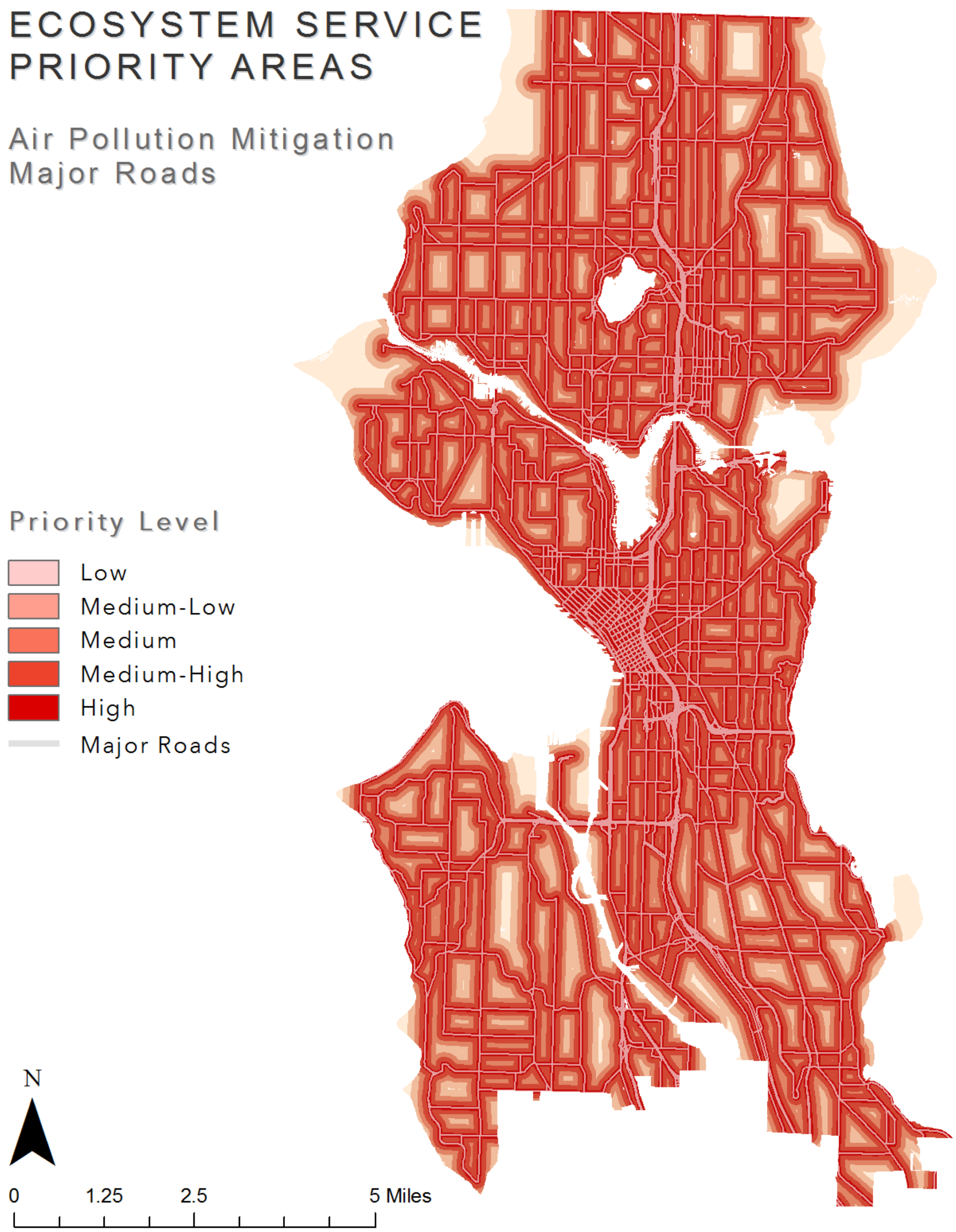

Figure 11: Priority level for air pollution mitigation need from major roads.

High Priority Locations

Most of the land are classified as medium-high priority indicating that there is a high demand and need for air pollution mitigation near major roads which green infrastructure can address. Overall, there is more land area with higher priority level for air pollution mitigation near major roads.

Highest priority areas are spread out across the city following the major roads used for the analysis. The closer to the road people are, the higher exposure there is to air pollution. Therefore, areas within a certain buffer distance of the road are prime areas for GI's air pollution mitigation service.

The result does not include actual data of air pollution levels for any specific contaminants. As discussed in the methodology, the air pollution data available was not robust enough to conduct interpolation across the city, therefore distance from major roads was used as a proxy. This proxy relies on the deposition rate of air pollution contaminants which has been widely studied, however it does not consider wind direction and speed. Additionally, this analysis does not include weighting roads based on traffic volumes and emitted air pollution particles by type of vehicle.

Public vs Private Ownership

In general, the ownership of land in high priority level areas is mainly privately owned. Most of the public land has a medium-high priority level which is also the priority level for most of the land area in the city. About 10% of the area classified as high priority l is on public land, and about 15% of the area with medium-high priority level is on public land. Most of this public land is probably sidewalks and roads which presents an opportunity for the city to install green infrastructure.

Land Use

In the high priority level, the two most prevalent land uses are residential and commercial. Interestingly, medium-high priority areas are mainly residential and institutional and public buildings. The institutional and public buildings would be an opportunity for the City of Seattle to start pushing as locations for the siting of GI to mitigate air pollution as they are places which they can develop on.

Air Pollution Mitigation from TRI Facilities

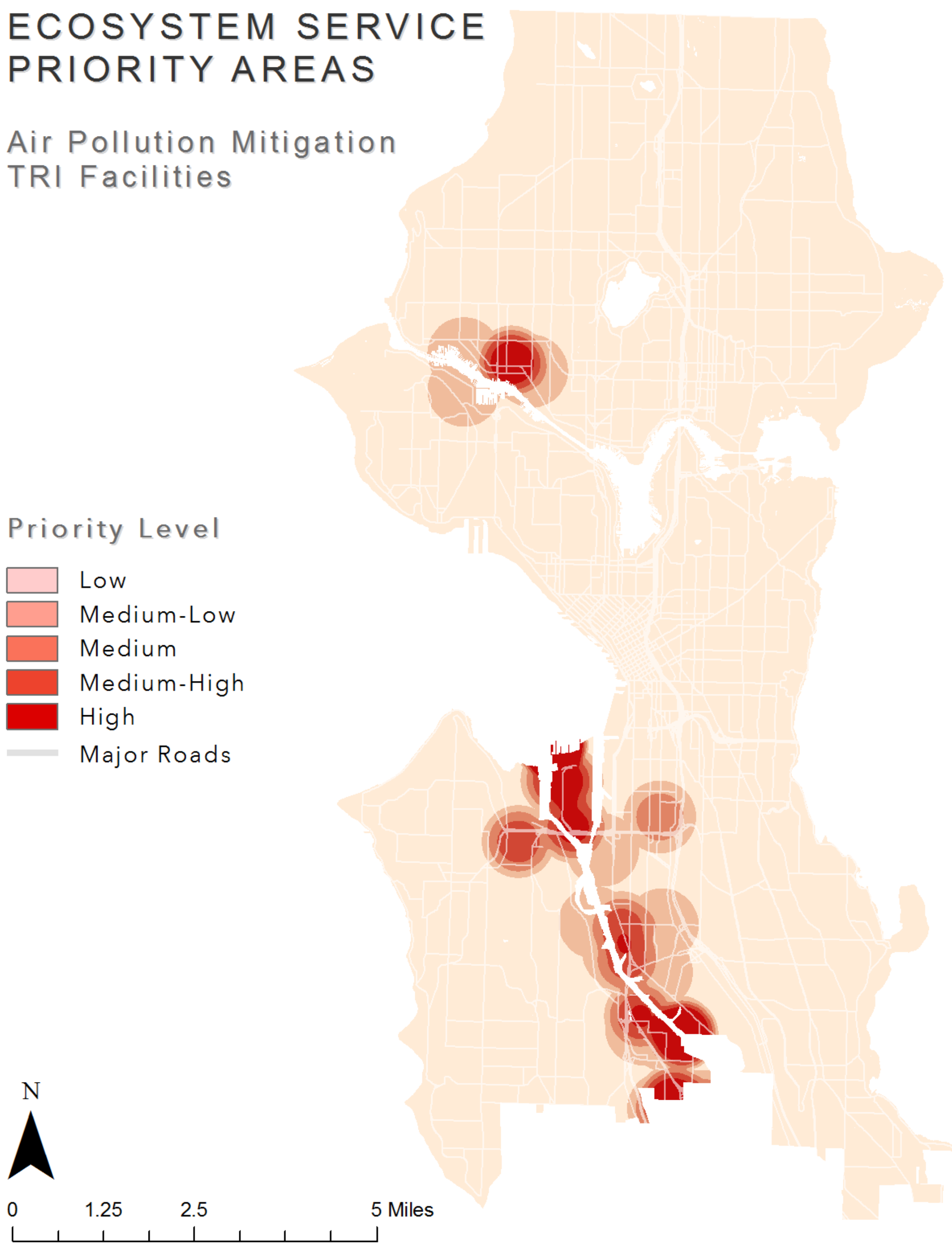

Figure 12: Priority level for air pollution mitigation need from toxic release inventory (TRI) sites.

High Priority Areas

Most of the land area is classified as low priority because most of the city is outside of the buffer distance set around the TRI facilities. The area of land with high or medium-high priority is very low, but that does not negate the fact that there still needs to be air pollution mitigation solutions installed. If anything, without including wind speed and direction and still ranking areas around the TRI facilities as high priority brings focus to where siting GI could do the most work. Even with wind speed and direction, the area around the facility will still be ranked as high priority for GI air pollution mitigation ecosystem service.

Highest priority areas are centered in the industrial district in the South and the manufacturing area in North Seattle. This is where most of the TRI facilities are located. The result does not include the movement of air pollution due to wind speed and direction. This could drastically change the distribution of pollution and where the high priority areas are. However, like the road air pollution data, the TRI facilities data were not robust enough to perform kriging or IDW to interpolate the data. Therefore, it is important to remember that this is just a simple model and does not represent real life air pollution needs.

Public vs Private Ownership

In general, the ownership of land in high priority areas is mainly privately owned, but a sizable percent of the total land area classified as high and medium-high priority are publicly owned. About 20% of the area with high priority level is on public land, and about 35% of the area with medium-high priority level is on public land. So far this poses a great opportunity for siting GI in these areas to provide air pollution mitigation ecosystem services.

Not including the public land area with low priority, most of the public land has a medium-high priority level. Thus, there is a strong need opportunity for the city to develop and install GI in these areas for air pollution mitigation.

Land Use

Since the TRI facilities are located in the industrial district in the South and the manufacturing area in North Seattle, it is expected that the land use with the most area classified as high priority is industrial. Interestingly, there are also other land use types (Commercial and residential) exposed to the air pollution emitted by the TRI facilities. This is very concerning as these are areas where the public would be exposed to toxic air pollutants, emphasizing the need for green infrastructure's benefit of air pollution mitigation.

Carbon Sequestration

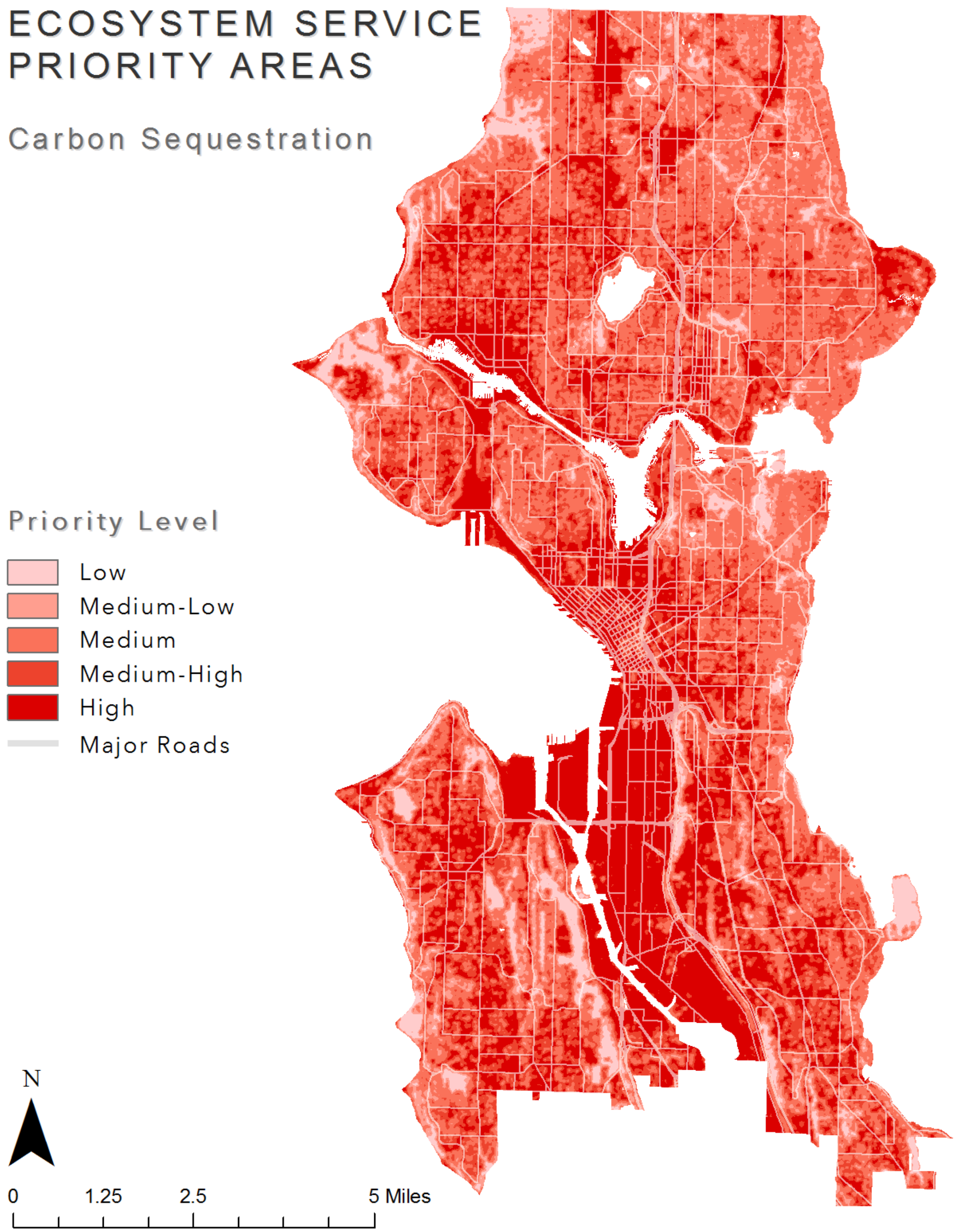

Figure 13: Priority level for carbon sequestration need.

High Priority Areas

There are distinct areas of high priority across the city. In North Seattle, the places that have a high need for carbon sequestration include Adams, Green Lake, Bitter Lake, Haller Lake, the middle of Lake City, middle of Northgate, and Sand Point. In Central Seattle, the downtown and Interbay areas have been classified as high priority. High priority areas in West Seattle include the industrial district and northern part. Finally, Southeast Seattle's Beacon Hill is also a high priority area for carbon sequestration.

The analysis calculated carbon sequestration rate of urban trees based from tree canopy cover. A limitation of this is that it ignores other types of green infrastructure and vegetation that can provide carbon sequestration services. Therefore, the results for this underestimate the carbon sequestration capacity across the city.

Public vs. Private Ownership

More than 50% of the city is classified as having at least medium priority for need of carbon sequestration. This is a strong indication that there is a huge potential and opportunity for Gi to provide this specific ES. Similar to previous ecosystem services discussed, there is a higher percentage of privately owned land in all of the priority level classifications. Still, about 15% of the area with high priority level is on public land, and the same percentage is classified as medium-high priority. There is more public land classified as high priority compared to the other levels. So far this poses a great opportunity for siting GI in these areas to provide more carbon sequestration.

Land Use

The land use distribution for the high priority level is more evenly distributed that it has been for the other ecosystem services discussed. Residential land still has the highest prevalence, but commercial and industrial land also makes up a sizeable portion. The area of institutional and public buildings is half that of the area of industrial land. Most of the transportation land, such as bridges, airports and hangers, are given a high priority for need of carbon sequestration.

Urban Heat Island Effect Mitigation

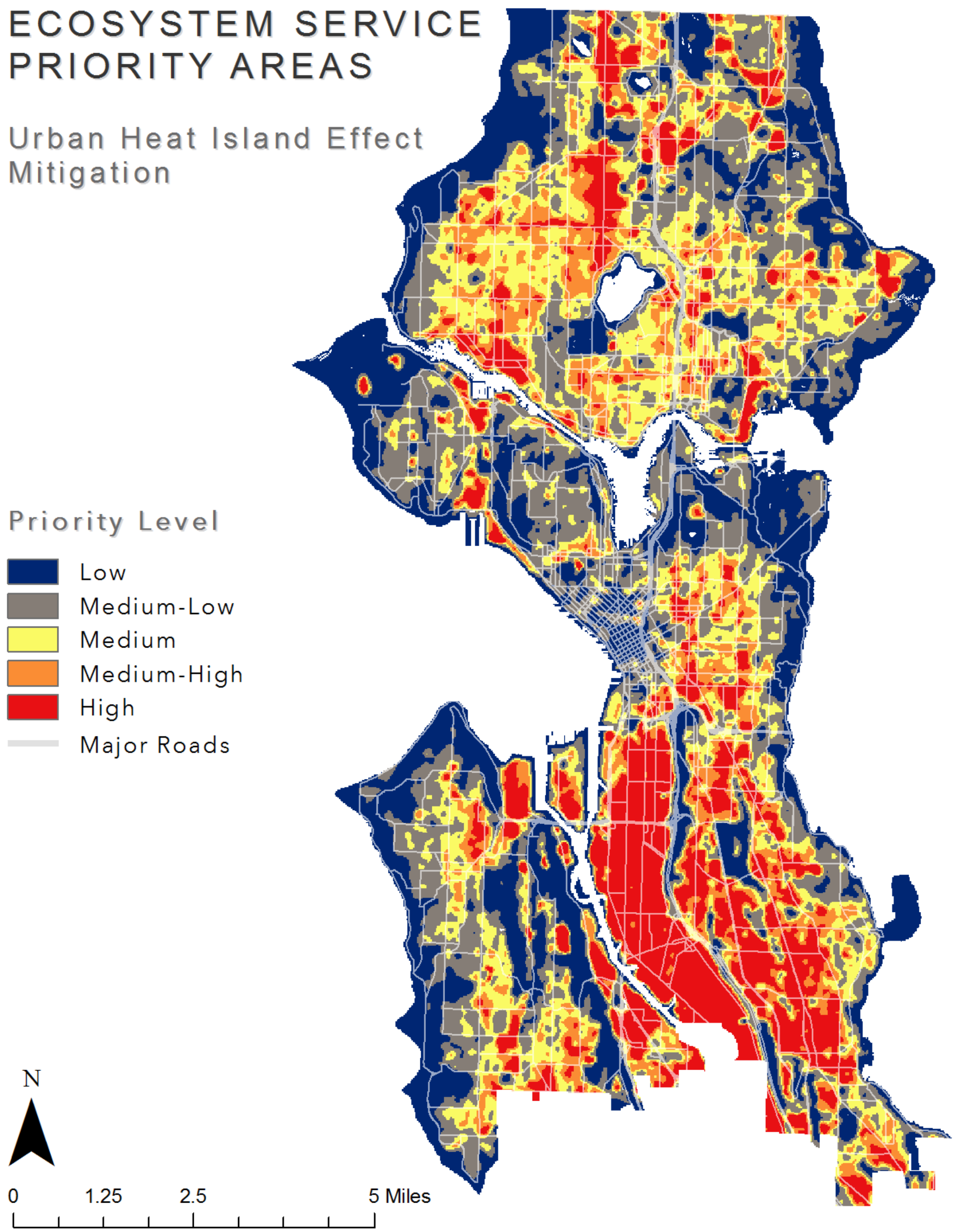

Figure 14: Priority level for urban heat island mitigation need.

High Priority Areas

In general, the central portions of the north and the south of Seattle are classified as high priority. Areas near the edges of the coast are not given high priority as the water and wind at the coast helps to decrease land surface temperature. Other areas that are classified as high priority in North Seattle include: Adams, Greenwood in Green Lake, the boundary of Bitter Lake and Haller Lake, middle of Lake City, middle of Northgate and Sand Point. Towards the center of Seattle is Interbay which is also designated as high priority. The industrial district and south of South Delridge and Roxhill also have a high need for urban heat island mitigation. Finally, the whole of Southeast Seattle except the borders and a small section the middle are in need for urban heat island mitigation.

The land surface temperature is only for one day (August 22) in the summer of 2017. A better analysis should include average land surface temperature across time using anniversary dates from the same satellite. Additionally, ambient air temperature can be different from land surface temperature and is the temperature which people feel when they are walking outside. Further research can use ambient air temperature and compare it to land surface temperature to see where the differences are in prioritized need for mitigation of the urban heat island effect.

Public vs Private Ownership

As is becoming a pattern among the ecosystem services discussed, there is a higher percentage of privately owned land in all of the priority level classifications. More than 50% of the city is classified medium or lower priority. However, there is still more land classified as high priority compared to medium-high. About 15% of the area with high priority level is on public land. Not including publicly owned land classified as low priority, there is more public land classified as high priority compared to the other levels. So far this poses a great opportunity for siting GI in these areas to provide urban heat island effect mitigation.

Land Use

Similar to the land use distribution for need of carbon sequestration, the land use distribution for high priority of urban heat island effect mitigation is more evenly distributed than it has been for the other ecosystem services. Residential land still has the highest prevalence, but commercial and industrial also make up a recognizable portion. The area of institutional and public buildings is half that of the area of commercial land.

Habitat Buffers

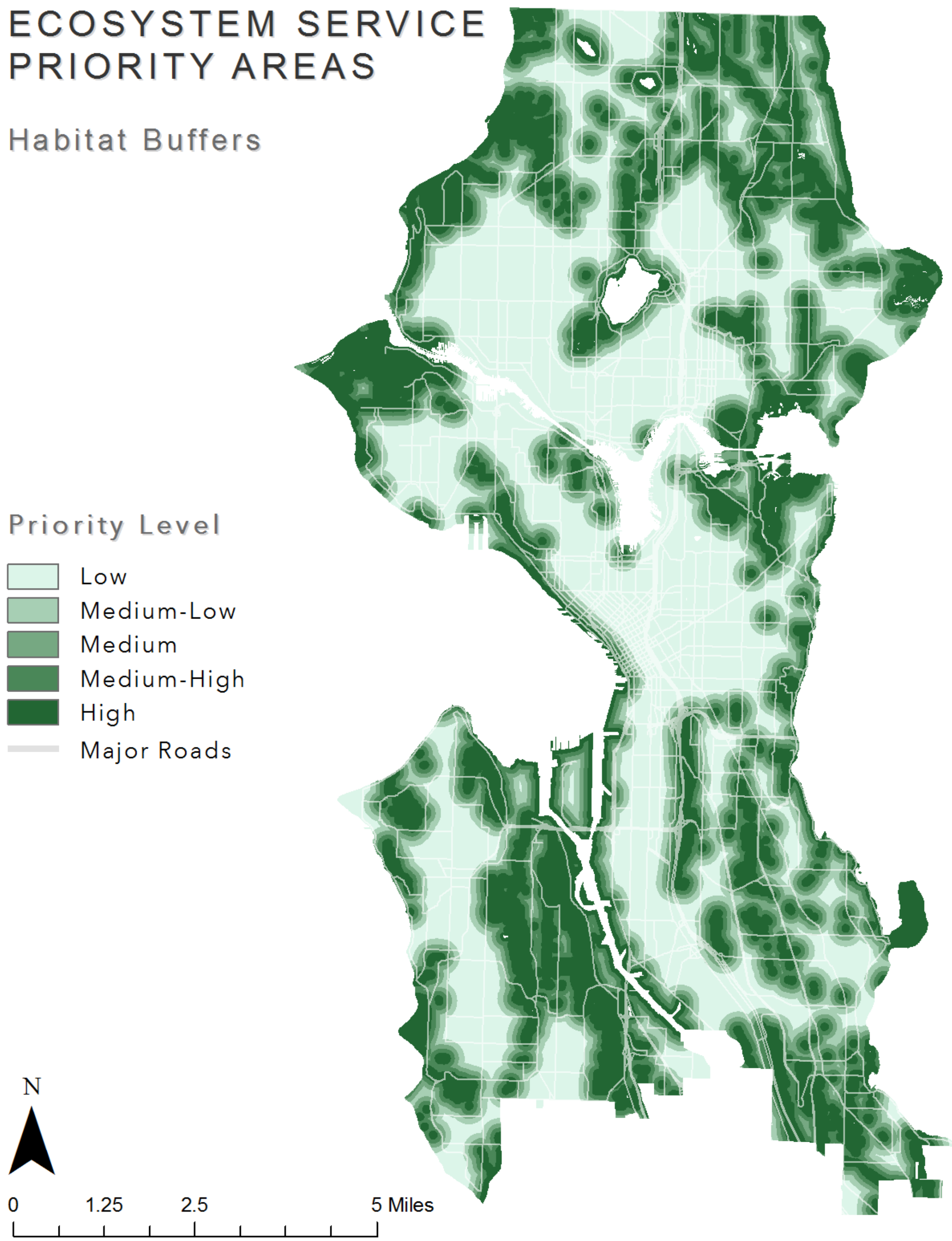

Figure 15: Priority level for habitat buffer need.

High Priority Location

In general, the north and south of Seattle has specific locations of high need for habitat buffers. High priority areas in the north include: Lake City and Northgate, Northwest, Lawton Park and Sand Point. The Central District and Montlake in central Seattle also has high priority levels. West Seattle highlights Delridge, while most of Southeast Seattle is classified as high priority.

This analysis didn't take into account specific species or levels of biodiversity. Some of the environmentally critical areas may have more importance over others due to higher biodiversity. This may affect how buffers at different locations are ranked because a biodiversity index would add a weight to the analysis.

Public vs Private Ownership

High priority or low priority classifications have about the same area of land, indicating that there is a high need for habitat buffers in specific areas while the rest is far enough from ecologically critical areas to have low priority. About 30% of the land classified as high priority for building a habitat buffer is public land. Compared to the other ES, this is the highest proportion of public to private land at a high priority level. Additionally, more than 50% of total public land is classified as high priority for building a habitat buffer. This poses a great opportunity for siting GI in these areas to help strengthen biodiversity through decrease of edge effects and habitat fragmentation.

Land Use

Residential land has the highest prevalence, while commercial, industrial, open space and recreation, and institutional and public buildings are close to equal in the high priority classification.

Access to Green Space

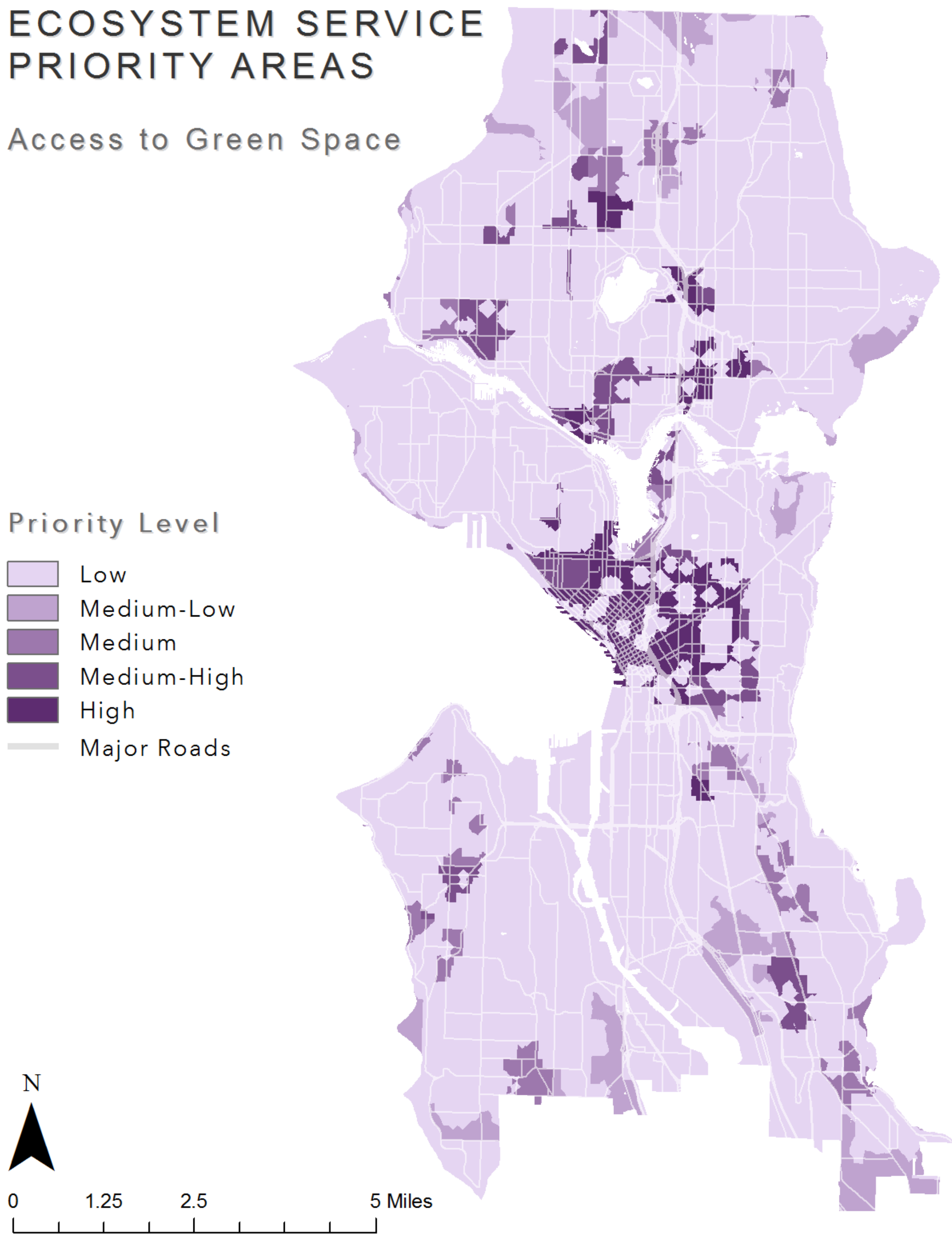

Figure 16: Priority level for access to green space needs.

High Priority Locations

High priority locations stick out strikingly in the downtown area, and the other urban villages where the distance to a park standard is at 1/8 mile. North Seattle high priority areas include: Bitter Lake and Greenwood, Roosevelt, Adams, Fremont and the University District. South Delridge and Roxhil, as well as Genesee are areas in West Seattle that also have a high priority for access to green spaces. In Southeast Seattle, the Holly Park area can also benefit greatly from green infrastructure improving access to green space there.

This analysis didn't take into account the quality and facilities of green spaces. In further studies, with the available data, weighting areas around green spaces as higher priority if they are not as high quality compared to parks.

Public vs Private Ownership

Low priority classification has the most land area which makes sense because most of the city is within reasonable walking distance (1/2 of 1/8 mile) to a park. It is only within some urban villages, where the standard is to give people access to a park within 1/8 mile where there is land classified as high priority.

Only 10% of the land classified as high priority is public land. This may be a barrier for the city to build parks and larger green infrastructure projects to allow all residents to have access to green spaces. There will need to be partnership with private land owners to bring about the change that is needed. However, apart from the low priority land, most of the public land is classified as medium-low need.

Land Use

Once again, residential and commercial land uses have the highest prevalence in the high priority classification.

Social Vulnerability

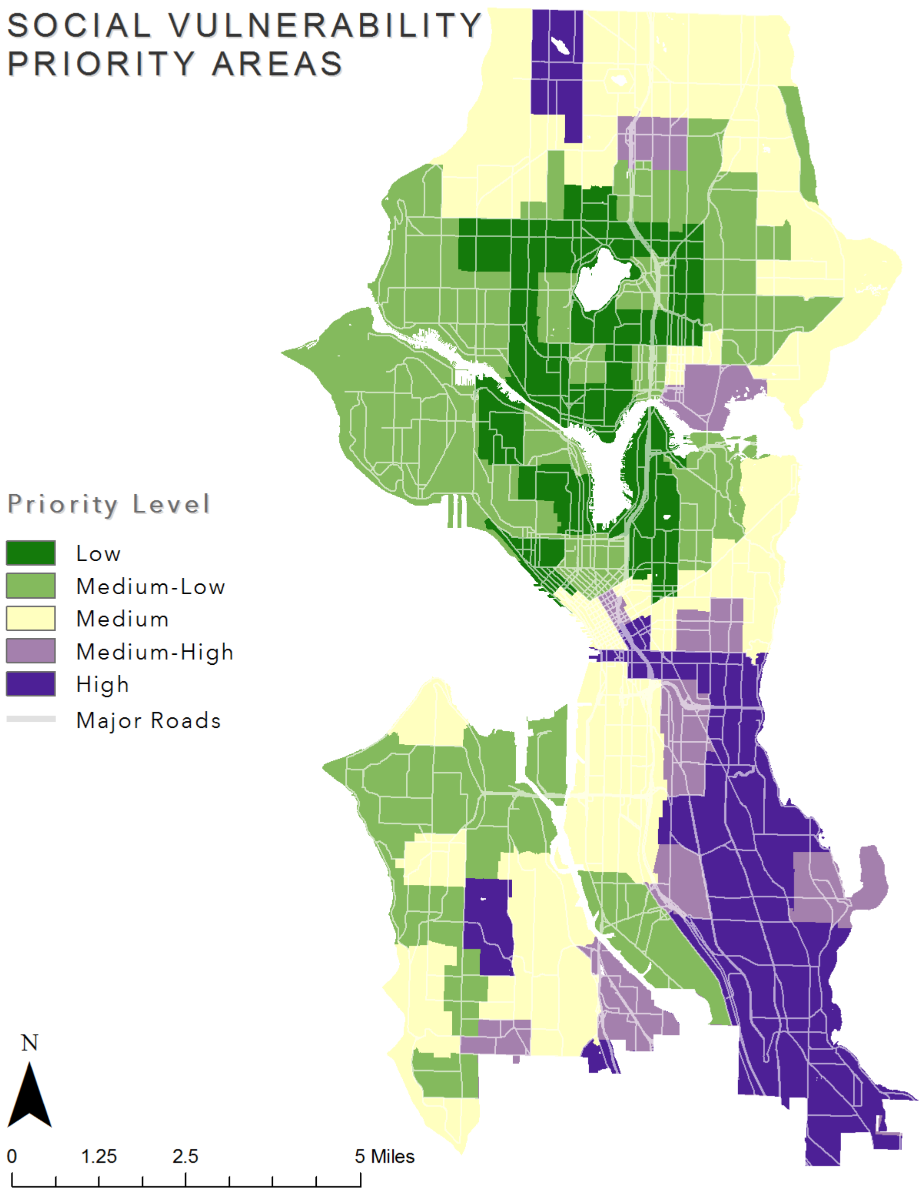

Figure 17: Priority level for green infrastructure need in socially vulnerable areas.

High Priority Locations

Bitter Lake and Haller Lake, North College Park, and University District are all high priority locations in the North of Seattle. West Seattle highlights High Point as a place of high social vulnerability. Additionally, all of Southeast Seattle has a highly vulnerable areas. As this analysis utilized an existing social vulnerability index the final result will not have detailed demographic information about the individual socio-economic factors that were included in constructing the index.

Public vs Private Ownership

Medium and medium-low priority has the highest percentage of land area. However, the next highest is the high-priority level. About 15% the land classified as high priority is public land.

Land Use

Residential and institutional and public buildings have the highest prevalence in the high priority classification.

2. Interactions Between Ecosystem Services

Overview

This section analyzes the equally weighted scenario by identifying high priority locations. I decided to run an equally weighted scenario without the social vulnerability layer to compare it to the equally weighted scenario with social vulnerability. The goal of this was to see how social vulnerability shifts the overall priority areas for green infrastructure benefits. This section also looks at areas of agreement between ecosystem services and compares it to the equally weighted scenario.

Analyzing the Equally Weighted Scenario

High Priority Locations

Based on the equally weighted scenario, high priority hotspots for green infrastructure benefit needs are:

- North Seattle:
    - Middle of LakeCity, Middle of Northgate
    - Adams
    - East border of Northwest
    - University District
- West Seattle:
    - South of South Delridge and Roxhill
    - Industrial District and Georgetown
- Central area:
    - Interbay and Downtown
    - Southeast Seattle (All)

Errors cumulated from the underlying layers are compounded in this final map.

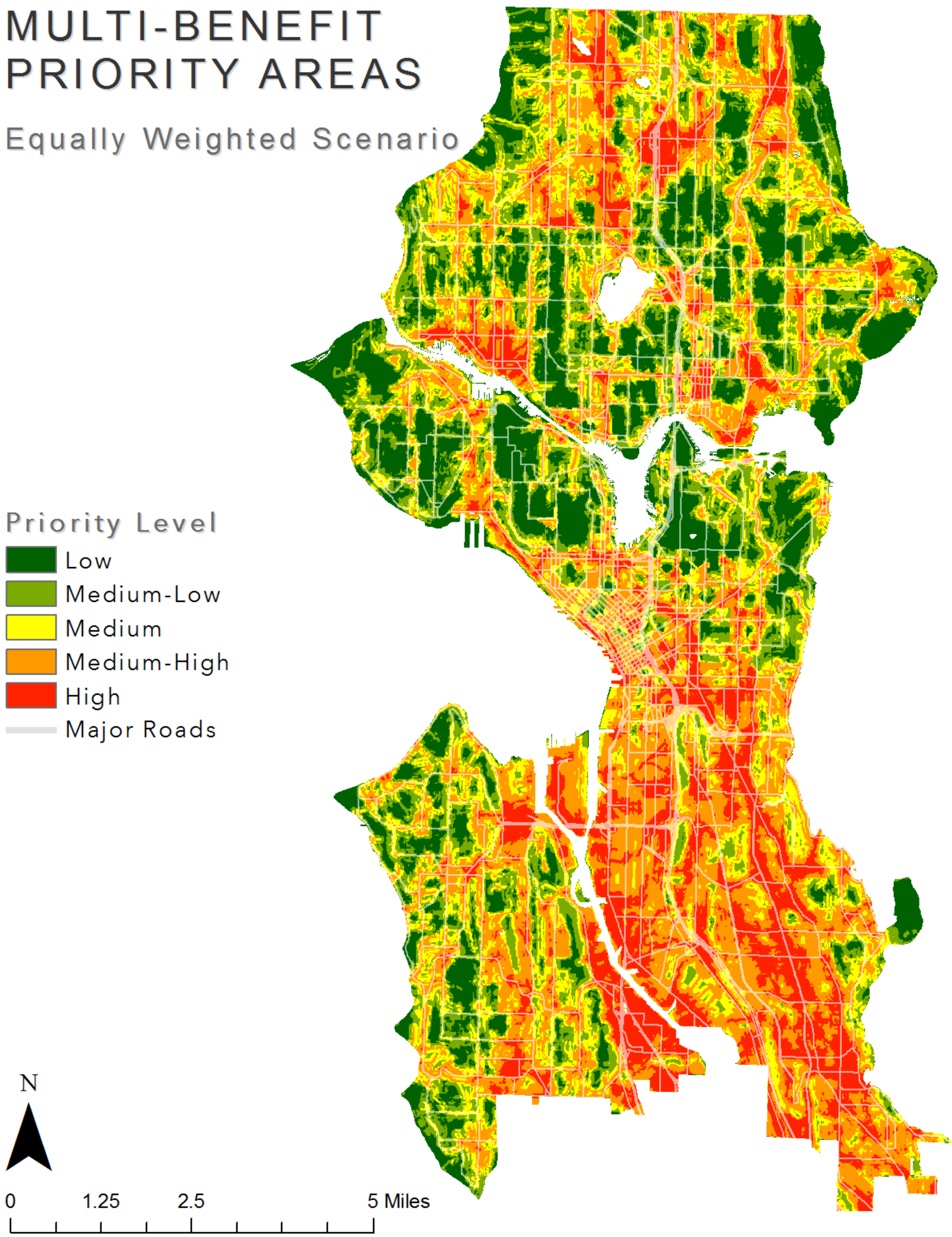

Figure 18: Equally weighted scenario of multi-benefit priority areas.

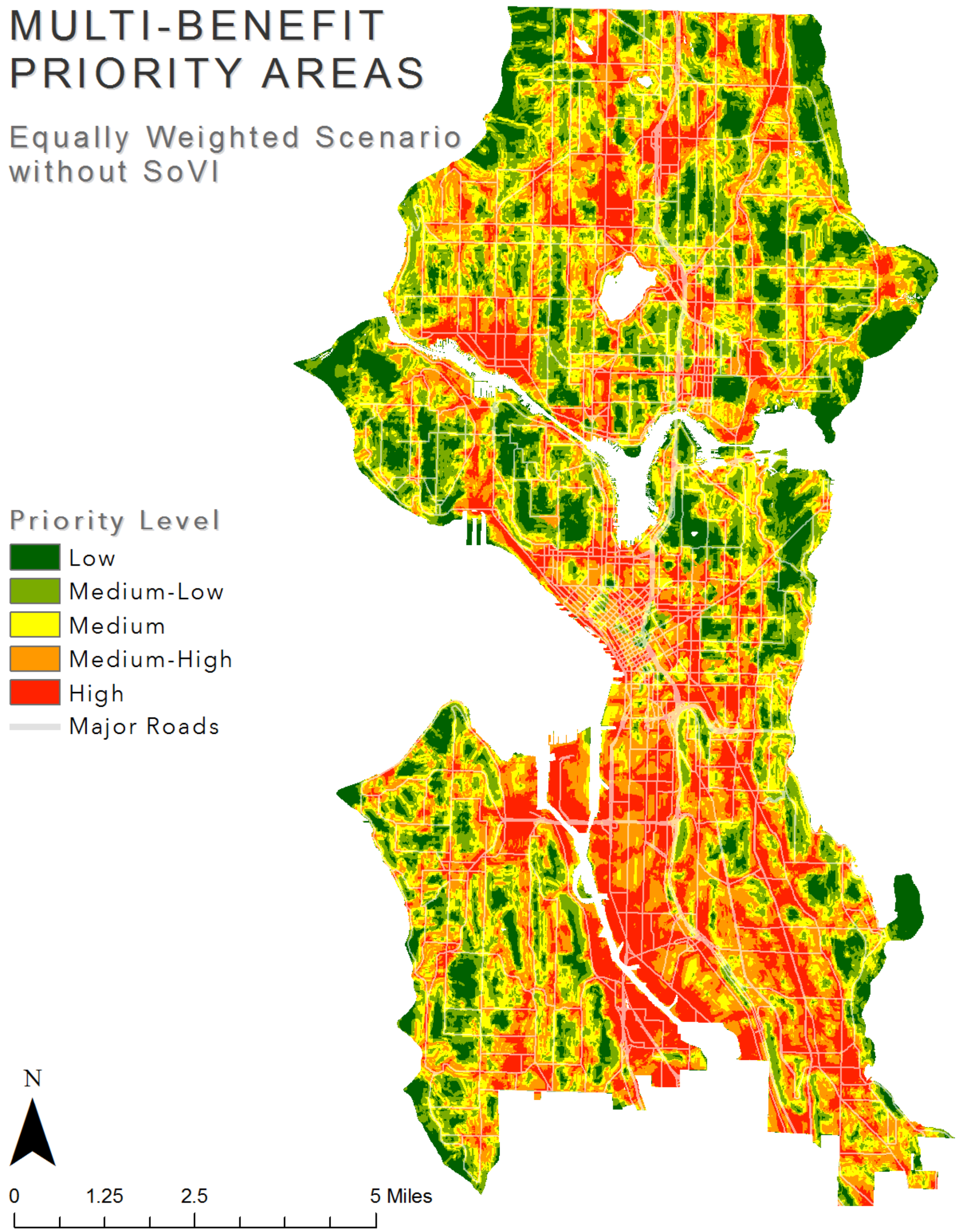

Figure 19: Equally weighted scenario of multi-benefit priority areas, not taking into account social vulnerability.

Shifts in Priorities: Social Vulnerability

Overall, high to medium-high priority level distribution is similar between the equally weighted scenario with and without social vulnerability. Including the social vulnerability layer results in more focus on areas which were identified as the high to medium-high priority areas in both maps. There are more low priority areas between islands of high to medium-high priority levels when social vulnerability is included in the scenario, especially in North Seattle. This makes it easier to distinguish distinct areas of multi-benefit priority areas for siting of GI.

The one area that increases in high and medium-high priority when including social vulnerability is Southeast Seattle. It looks like medium-high priority areas expand which makes sense if we look back to the individual social vulnerability priority areas. It shows that all of Southeast Seattle is high priority area for GI ecosystem services.

Interestingly, the equally weight scenario without social vulnerability also highlights Southeast Seattle as one of the key places that can greatly benefit from GI ecosystem services. This suggests that there is underlying social and environmental justice issues at play, which the city needs to take into account when going forward to expand green infrastructure across the city. Location of new projects and their recipients are important questions that need to be answered through research and analysis.

Another concern for residents is that the industrial district also has high priority need for ecosystem services. Residents and citizens may be concerned that such a high priority for the industrial area may draw investments away from the neighborhoods that need it, too. Therefore, the city should be careful in planning and prioritizing locations of GI projects.

Areas of Agreement between Ecosystem Services

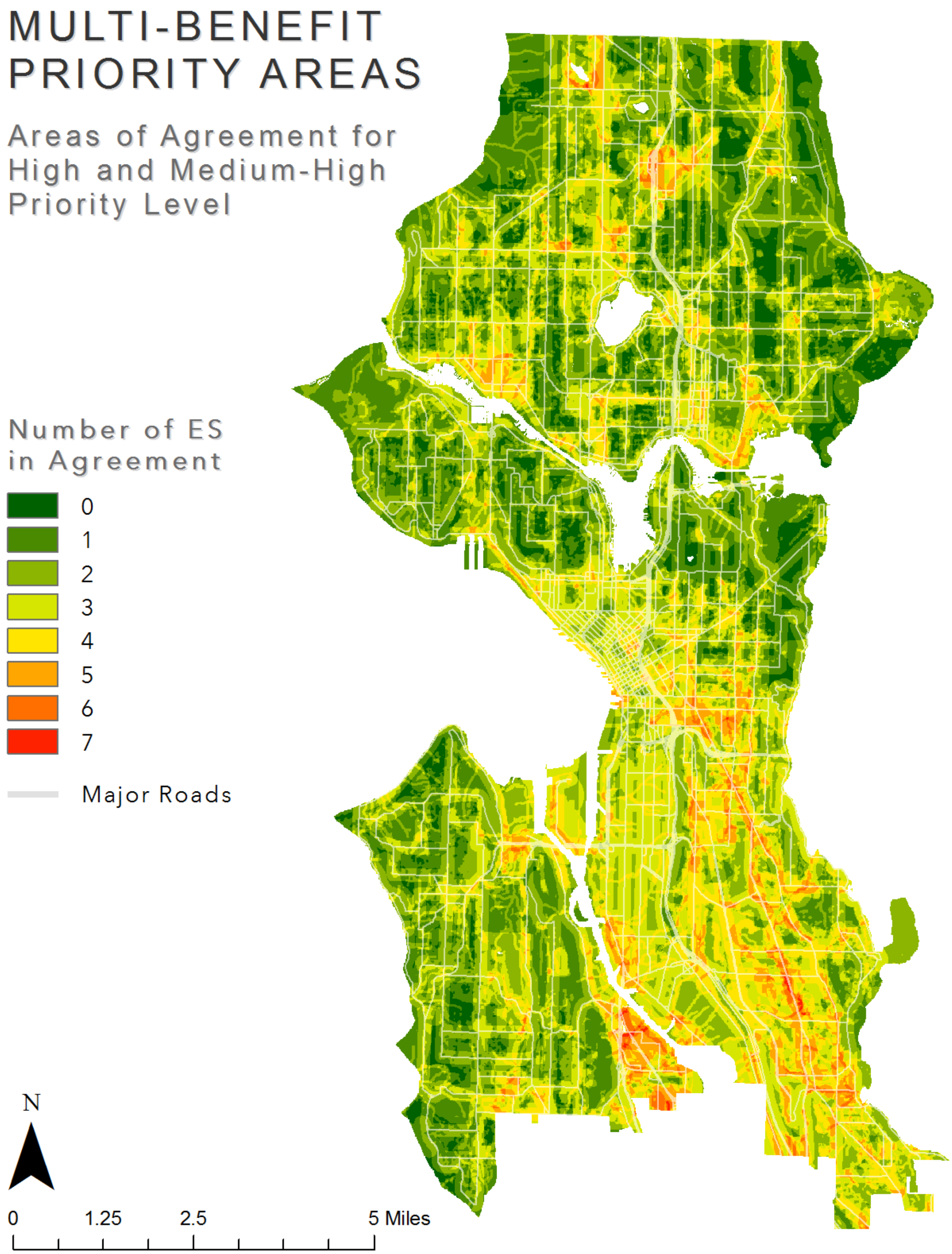

Figure 20: Areas of agreement between individual ecosystem service priority need areas.

Areas of Agreement and Equally Weighted Scenario

The equally weighted scenario allows us to get a general idea of where high to medium-high priority areas are when overlaying the 7 ES and social vulnerability; however, it doesn't tell us how many ES are a high or medium-high priority at a single location. The map showing areas of agreement for high and medium-high priority illustrates how many ES ranked as high or medium-high priority are met on a spatial scale. For example, a value of 0 means that none of the ES included in the model had a high or medium-high priority level at that location. A value of 7 means that 7 of the ES included in the model had a high or medium-high priority level at that location. The general spatial distribution of areas with the most number of ES ranked high or medium-high is similar to the equal weight scenario, but there is a more detail for determining potential locations for GI would address several needs for ES.

The areas identified to have at least 5 ES met if GI were sited there are mostly in Southeast Seattle. Within Southeast Seattle, the area between Holly Park and Brighton has a high priority for need of GI ES. The Atlantic area East of downtown is also a key priority area for siting of GI to maximize multi-benefit ES. In West Seattle, South Park has some areas that would address 6 or 7 ES needs if GI were located there. North Seattle has a few locations that are also highlighted as places where many of the ES needs would be met with GI. These areas include: north of Bitter Lake, between North College Park and Maple Leaf, Adams, and University District.

A limitation is that this analysis does not identify specifically which ES at a specific point have a high or medium-high priority.

Public vs Private Ownership

Most of the land area in Seattle has 2 ecosystem services in agreement (Figure 21). There is still a lot of land that would have more than one ecosystem service in agreement. Therefore, when siting green infrastructure the City of Seattle has a huge opportunity to address several needs at once and this means cooperation between different departments to reach their individual goals needs to be supported and encouraged.

Similar to the section discussing individual ecosystem service results, because there is proportionally more privately-owned land across Seattle, there is more privately-owned land across all agreement levels than publicly-owned land. However, there is publicly-owned land where multiple ecosystem services can be provided for if green infrastructure were sited there, illustrating an untapped opportunity for the City of Seattle. About 20% the land classified as having 2 ecosystem services in agreement is on public land. 37% of publicly owned land have 2 ecosystem services in agreement. The percent of land with three ecosystem service in agreement and the percent of land with only 1 ecosystem service ranked high priority is about the same at 23% and 24%, respectively.

Land Use

Below is a list of the top two land uses for areas in agreement with at least 5 ecosystem services (Figure 22):

- 7 ES in agreement: Commercial and Residential
- 6 ES in agreement: Commercial and Residential
- 5 ES in agreement: Commercial and Residential
- Combine 5 to 7 ES in agreement: Commercial (500 acres) and Residential (830 acres), Institutional and public buildings have 200 acres which is probably around the university district.

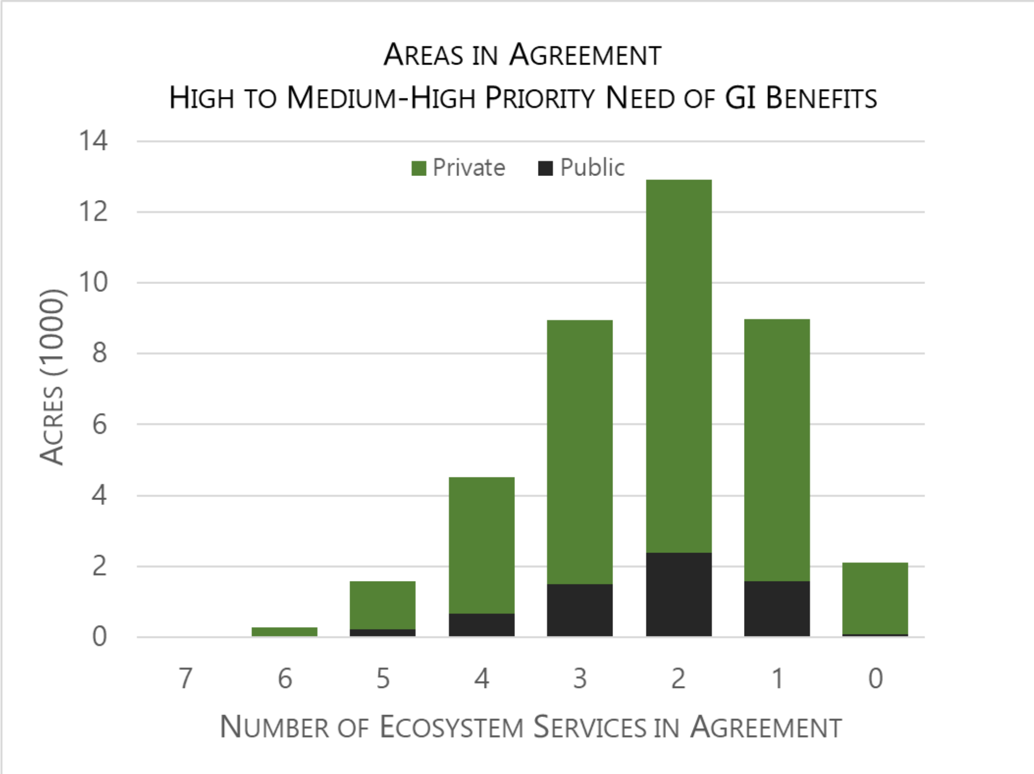

Figure 21: Areas in agreement by public or private ownership.

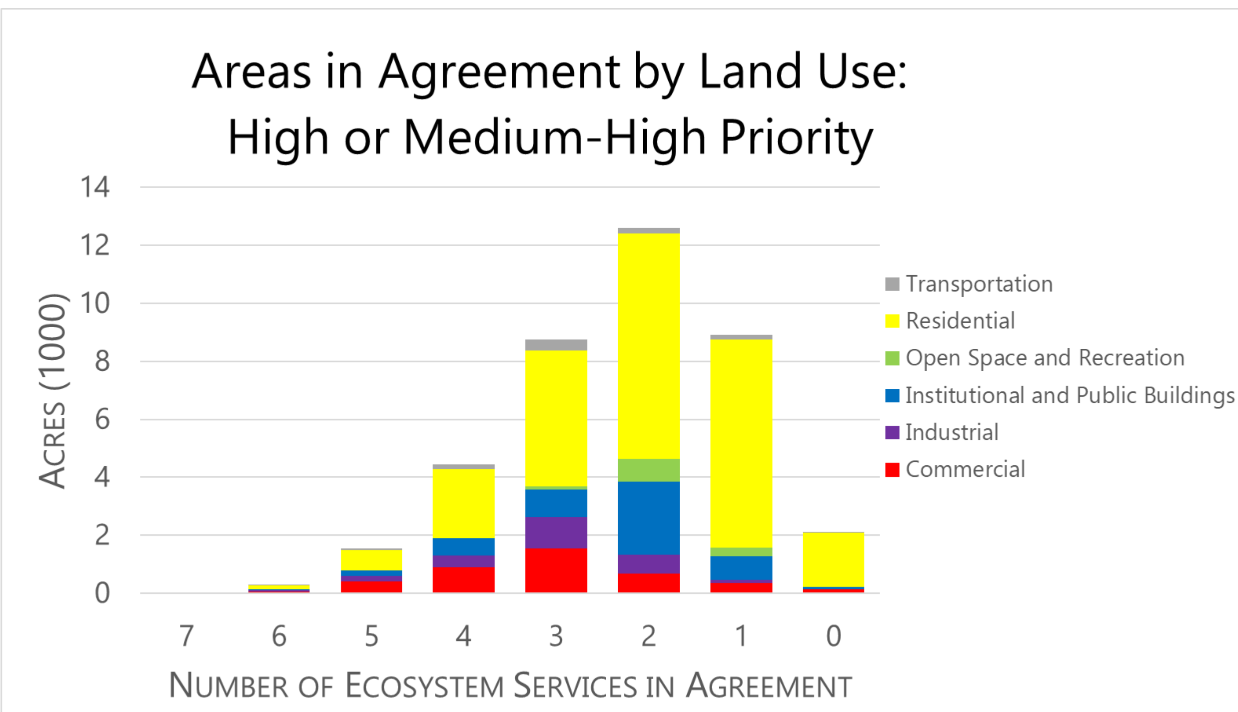

Figure 22: Areas in agreement by land use categories.

3. Comparing Weighted Scenarios

Ecosystem Service Weighted Scenario vs. Equally Weighted Scenario

How does each weighted scenario differ from the equally weighted scenario? How does the weight shift priorities/need?

Overall, section 1 and 2 show that individual unweighted ecosystem service priority areas have similar high priority distributions compared to the equally weighted scenario. Many of the hotspots for high priority in the equally weighted scenario are still present in the individual unweighted ecosystem service priority areas, just either given more priority or a little bit less. Relatively, even with slight shifts in priority away from specific hotpots, they are still considered higher priority areas compared to the surrounding area. However, comparing individual unweighted ecosystem service priority areas to the equal weighted scenario does not give insight on how priority areas shift when different ecosystem services are given more priority. How each weighted ecosystem service scenario differs from the equally weighted scenario is discussed below, as well as how priorities are shifted when one ecosystem service is weighted above the others.

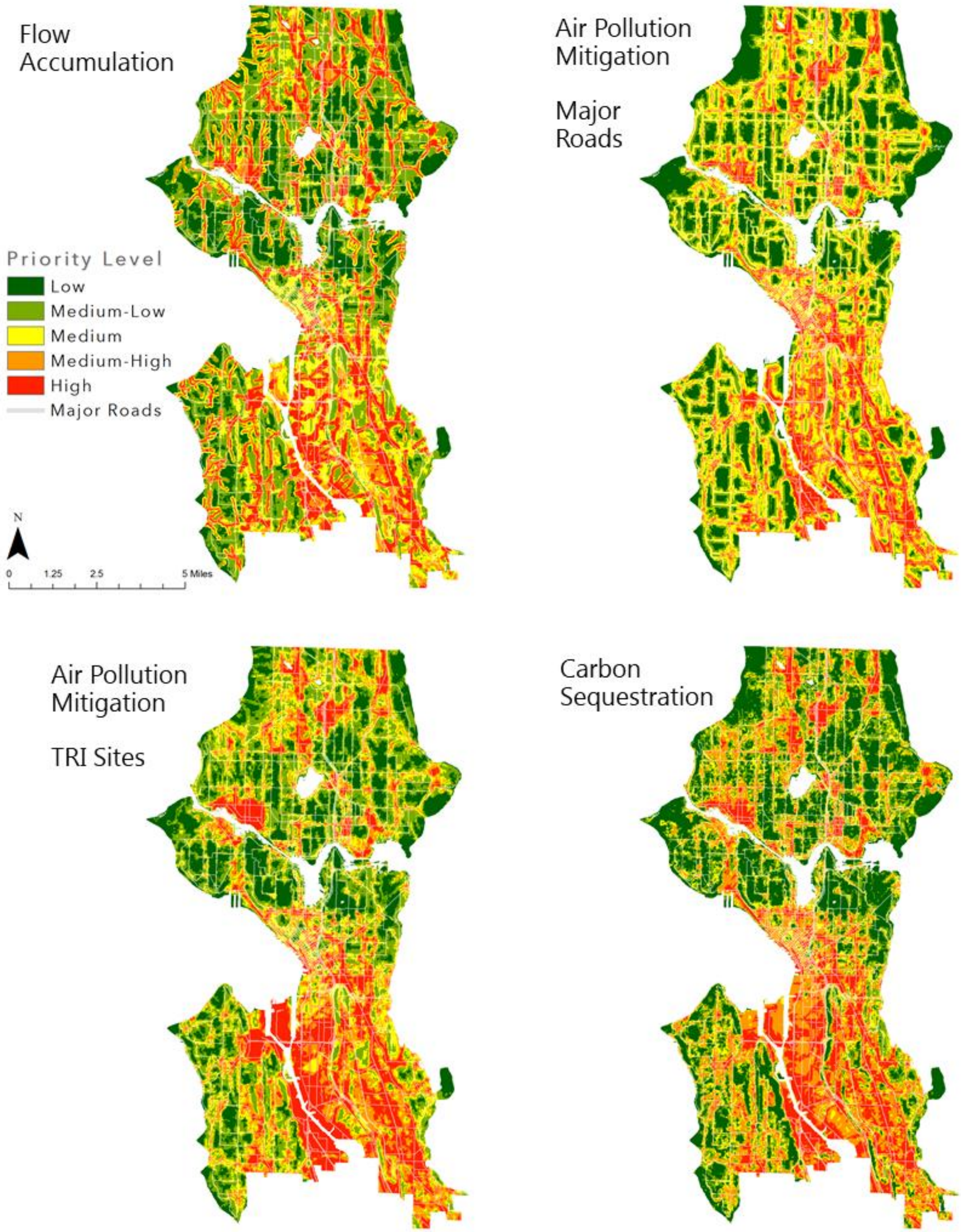

Figure 22: Multi-benefit priority areas according to weighted scenarios.

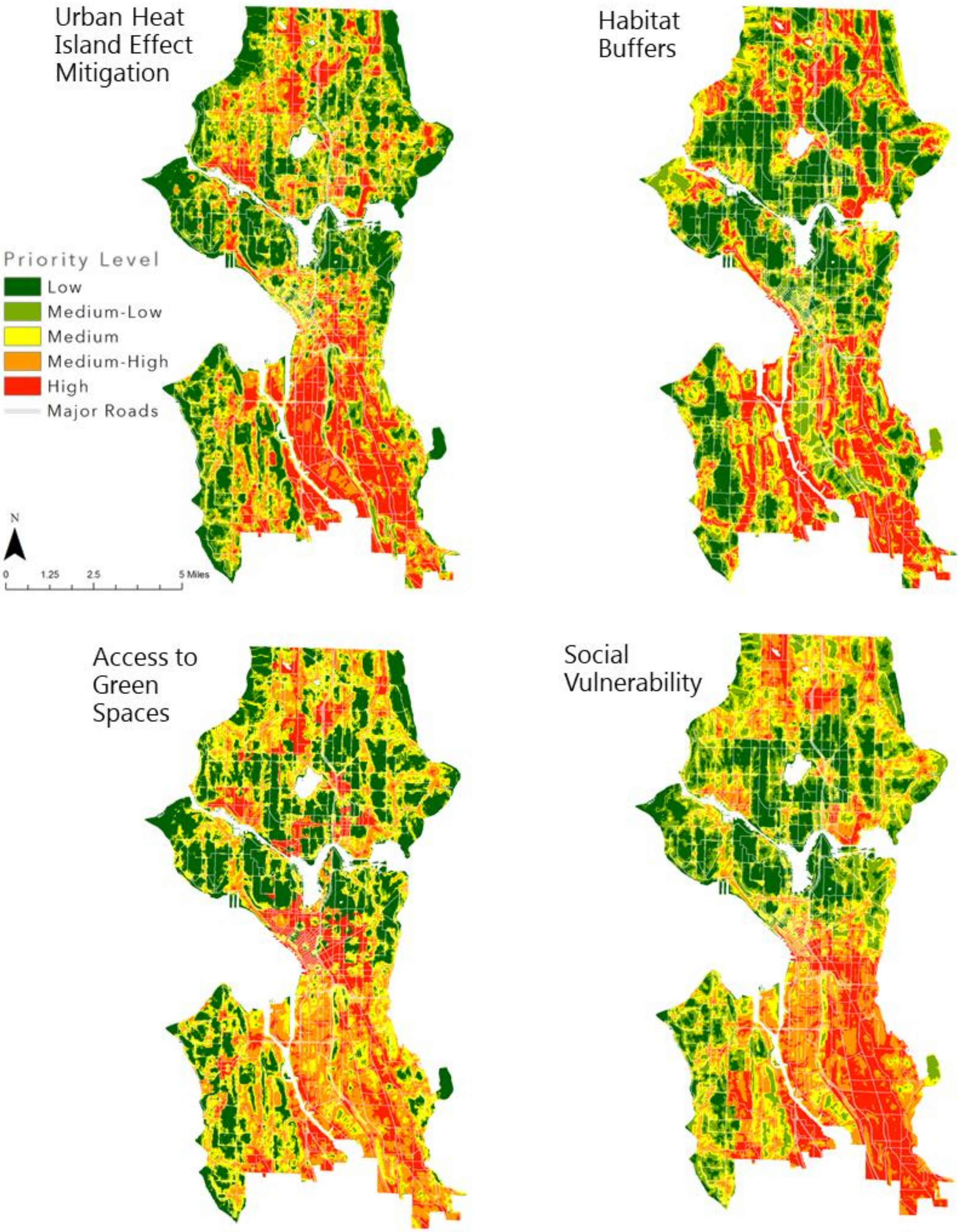

Figure 23: Multi-benefit priority areas according to weighted scenarios.

Flow Accumulation Mitigation

Comparing the equally weighted scenario (Figure 18) to flow accumulation weighted scenario (Figure 22), the streams of accumulated flow are obvious in the equally weighted scenario, especially the industrial district. These patterns are emphasized even more in the flow accumulated weighted scenario and it shifts the priorities to the center of the high priority areas reflected in the equal weighted scenario. Overall, the spatial distribution of high and medium-high priority level is similar but more distinct in the flow accumulation weighted scenario.

Areas that are given higher priority in the flow accumulation weighted scenario than in the equal weighted scenario are mainly on the west coastline of Seattle. For example, in North Seattle the North Beach/Blue Ridge area has more areas given a high priority. Just north of that along the coast at Broadview, the area if given a higher priority when flow accumulation is emphasized compared to the equal weighted scenario.

Air Pollution – Major Roads

Similar to the flow accumulation weighted scenario, the major roads weighted scenario (Figure 22) also puts more emphasis and priority on areas that are ranked high priority in the equal weighted scenario. The higher weight of major roads shifts priorities away from the surrounding of medium-high priority areas; there is a distinct loss of land classified as medium-high priority. For example, the Greenwood area is mostly high or medium-high priority in the equal weighted scenario, however in the major road weighted scenario, most of the area is either high priority or low priority. The same can be said for the industrial district and Southeast Seattle.

Air Pollution – TRI Facilities

The distinct difference is the greater emphasis and more high priority land in the industrial and manufacturing areas of Adams in North Seattle and the industrial district in South Seattle (Figure 22). This is because the industrial and manufacturing facilities are located in these areas. Prioritizing air pollution from TRI facilities does not shift the priority for the rest of Seattle. There is a slight decrease in medium-high priority areas in North Seattle, but not a drastic change in priority.

Carbon Sequestration

The main difference observed is the loss of medium-high priority in Southeast Seattle, Southwest Seattle, and Northeast of the downtown area (Figure 22). Medium-high priority areas in these locations look have shifted to lower priority areas for need of carbon sequestration. In contrast, there are more high priority areas in the industrial district and Interbay.

Urban Heat Island Effect Mitigation

The urban heat island (UHI) mitigation weighted scenario (Figure 23) brings higher priority to South Seattle. Specifically, the industrial district and Southeast Seattle are given high-priority for a larger area compared to the equal weighted scenario. For the rest of Seattle, there is also a decrease in priority in the UHI mitigation weighted scenario for areas that were medium-low priority.

Habitat Buffers

Weighting the need for habitat buffers more than other ecosystem services noticeably shifts higher priority to environmentally critical areas, and away from other areas (Figure 23). In North Seattle, areas that were medium-low areas have now shifted to low priority, while medium-high priority areas have shifted to high priority. The shift in priority is slightly different in Central Seattle around the downtown area. Only a small amount of area is left as high priority, while all other classes have shifted to a lower priority level. The industrial area also shows this change in priority levels except for the coastline. In Southeast Seattle, there is a clearer distinction between high and low priority areas, where as in the equal weighted scenario most of the area was classified as high or medium-high priority. Therefore, there is more low priority areas in Southeast Seattle when giving higher weight to habitat buffers than in the equal weighted scenario.

Access to Green Space

There is an obvious shift of priority to the downtown area when access to green space is weighted higher than the other ecosystem service scenarios (Figure 23). Additionally, it looks like there priority has shifted away from the industrial district and Southeast Seattle as the land area for high and medium-high priority is less than in the equal weighted scenario. In North Seattle, there is also a shift of priority towards Adams, University District, Fremont, and east of Greenwood. A decrease in priority can be seen for medium-high priority areas that are now medium priority as seen by the increase in dark green areas.

Social Vulnerability

There is a shift in high priority to Southeast Seattle, Bitter Lake in North Seattle, and High Point in Southwest Seattle (Figure 23). Areas which have decreased in priority include Adams in North Seattle and the Industrial District. These are industrial and manufacturing areas; by giving more weight to socially vulnerable populations the priority for addressing ecosystem service need in residential areas is increased, while it is decreased in industrial and manufacturing villages.

Comparing Between Ecosystem Service Weighted Scenarios

How do the weighted scenarios differ from each other? How does increasing the weight of an individual ecosystem service shift priorities and need for green infrastructure?

<u>Southeast Seattle</u>

Ecosystem services that individually shift higher priority to Southeast Seattle when weighted higher than other benefits include urban heat island effect mitigation, carbon sequestration, and social vulnerability (Figure 22 and 23). Those that result in lower priority for Southeast Seattle when weighted higher than other benefits include flow accumulation mitigation, air pollution mitigation from major roads, habitat buffers, and access to green space. Weighting air pollution mitigation from TRI facilities higher than other ecosystem services does not noticeably impact the priority levels in Southeast Seattle

<u>Industrial District and Manufacturing Villages</u>

Higher priority is given to industrial and manufacturing areas when air pollution mitigation from TRI facilities, carbon sequestration, and urban heat island mitigation are each weighted higher than other ecosystem services (Figure 22 and 23). However, lower priority is given to these areas when flow accumulation mitigation, air pollution mitigation from major roads, habitat buffers, access to green space, and social vulnerability are each weighted higher than other ecosystem services.

<u>North Seattle</u>

In the very North of Seattle consisting of Northgate, Lake city, and Northwest, priority increases when habitat buffers, access to green space, and social vulnerability are each weighted higher than other ecosystem services (Figure 22 and 23). Overall, all other scenarios leave this area without noticeable differences in priority level except for giving more focus to already high priority areas and shifting medium-low priority to low priority.

Preliminary Observations of Synergies and Tradeoffs

Synergies

Based on these observations, it is hypothesized that there could be some synergies between carbon sequestration and urban heat island mitigation. For all three spatial areas, they are placed in the same group. In Southeast Seattle and the industrial and manufacturing areas, both ecosystem services shifted priorities higher; while in North Seattle they both did not influence distinguishable change in priorities.

Another possible pair of ecosystem services in synergy is habitat buffers and access to green space. In Southeast Seattle and the industrial and manufacturing areas, both ecosystem services shifted priorities lower; while in North Seattle they both shifted priorities higher.

Flow accumulation mitigation and air pollution mitigation from major roads also display synergy in decreasing priorities in Southeast Seattle and the industrial and manufacturing areas, while not producing visible changes in North Seattle.

Tradeoffs

Potential tradeoffs will be derived from analyzing the shift in priorities of ecosystem services weighted scenarios in Southeast Seattle and the industrial district and manufacturing areas. There are potential tradeoffs between urban heat island mitigation and carbon sequestration which increased priority levels in the areas of interest, and four other ecosystem services (flow accumulation mitigation, air pollution mitigation near major roads, habitat buffers, and access to green spaces) which decreased priority levels.

While it is difficult to clearly see the synergies and tradeoffs between ecosystem services, this discussion helps to provide some background for the spatial statistics results in the next section.

4. Synergies and Tradeoffs

Spatial Statistics: Band Collection Statistics

Are there any pairs of ecosystem benefits that have a positive relationship (both have high or low need for green infrastructure) or a negative relationship (one has a high need while one has a low need)?

Figure 24 shows the correlation coefficient results from using Band Collection Statistics in ArcGIS. The correlation coefficient ranges from -1 to 1, with -1 as a strong negative correlation and 1 as a strong positive correlation. As predicted in the previous section, there is a relatively strong positive correlation (0.61) between carbon sequestration and urban heat island mitigation compared to other pairs of ES. This aligns with what is expected as areas with less vegetation and thus less carbon sequestration would have higher land surface temperature and be subject to the urban heat island effect. A higher rate of carbon sequestration, which means more vegetation, would have lower land surface temperatures.

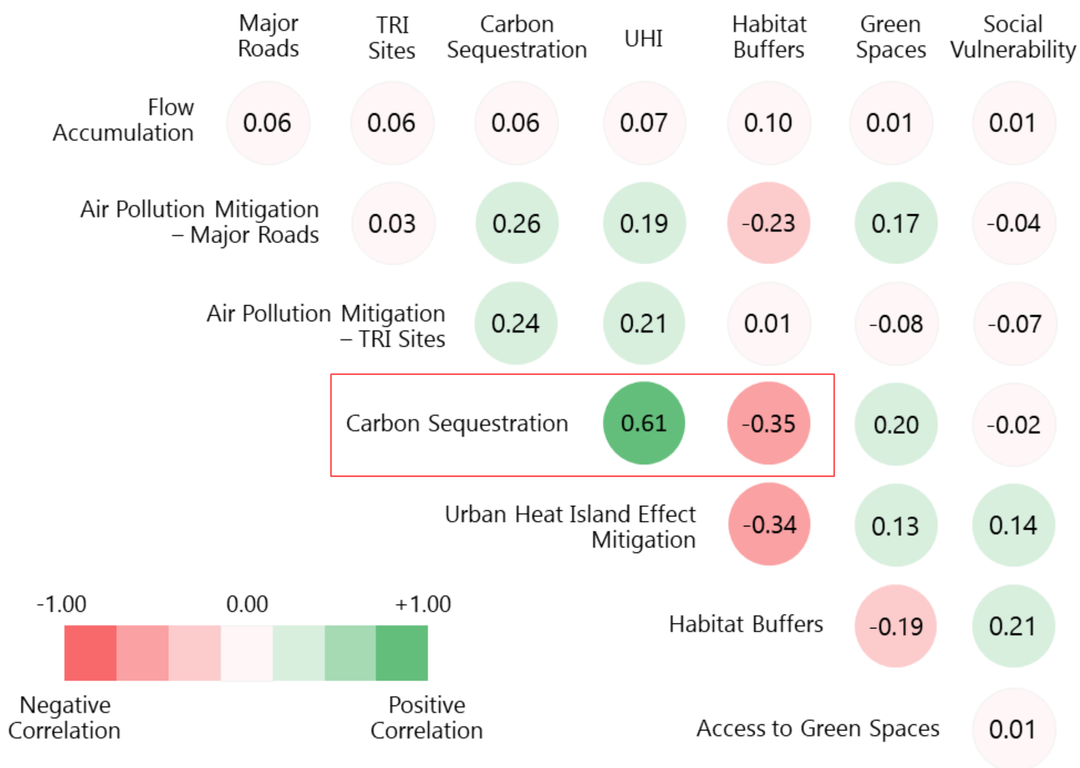

Figure 24: Band collection statistics results from ArcGIS. The red box indicates the pair of ecosystem services that was analyzed for spatial correlation in GeoDa using bivariate local Moran's I.

Surprisingly, there is a relatively weak negative correlation (-0.18) between habitat buffers and access to green space, where as in the visual interpretation of synergies it was observed that this pair of ecosystem services had a positive correlation. When looking at the individual ecosystem service priority area maps, this makes sense because in some areas, such as North Seattle and Southeast Seattle there is synergy of high priority areas for both ecosystem services. However, in the downtown area there is an obvious tradeoff. Therefore, the discrepancy is because the results in Figure 24 do not differentiate correlation spatially, while visual observations were based on two locations.

Another ecosystem service pair that was predicted to have a positive correlation but does not have any correlation from the results in Figure 24 is flow accumulation mitigation and air pollution mitigation near major roads. Comparing the individual ecosystem service priority area maps does not help in this interpretation as they both cover much of the city. This is where spatial correlation results will be helpful in clarifying tradeoffs and synergies between ecosystem service pairs.

A tradeoff between ecosystem services that was predicted in the previous section was carbon sequestration and habitat buffers. This is supported by the results in Figure 24 because this pair has a relatively strong negative correlation (-0.35). Knowing that carbon sequestration was calculated based on tree canopy cover, it makes sense that there is a negative correlation. Areas of low need for carbon sequestration (high tree canopy cover) would be near environmentally critical areas (forests or wildlife habitat areas) with high tree canopy cover. This can be observed by looking at the individual ecosystem service priority maps: areas of high priority for carbon sequestration (areas with low tree canopy cover) have a spatial pattern that is opposite of where high priority areas are for habitat buffers.

Spatial Statistics: Bivariate Local Moran's I

Based on the Band Collection Statistics findings, the bivariate local Moran's I was run on two pairs of ecosystem services to further analyze the spatial correlation: 1) carbon sequestration and urban heat island effect, and 2) carbon sequestration and habitat buffers. To reiterate from the methods section, a bivariate spatial correlation analyzes the correlation between one variable and the spatial lag of another. When deciding which variable to compare to the spatial lag of another, it is important to remember that spatial correlation investigates how neighbors affect a central location (GeoDa n.d.).

Carbon Sequestration and Urban Heat Island Mitigation (Positive Correlation)

I wanted to observe the effect of carbon sequestration need (which is linked to percent tree canopy cover) to land surface temperature (or need or UHI mitigation) at a central location. Therefore, the bivariate spatial correlation analyzed the correlation between urban heat island mitigation and the spatial lag of carbon sequestration.

The Moran's I is 0.41 (Figure 25a) indicating that there is a high-high or low-low cluster relationship. Looking at Figure 25, there are indeed more high-high and low-low spatial clusters than high-low and low-high spatial outliers in the cluster map. The significance map shown in Figure 25a illustrates locations with different levels of significance; this shows that the majority of the spatial clusters are significant at the 0.001 level. In fact, Figure 25a shows that the correlation between urban heat island mitigation need and the spatial lag of carbon sequestration is spatially significant in most areas at the 0.001 level.

These results support the findings from Band Collective Statistics where a relatively strong positive correlation (0.60) was found between carbon sequestration and urban heat island effect. However, the cluster map illustrates that even though there is an overall positive correlation there are also areas with a significant negative correlation. Nevertheless, the cluster map helps to identify areas where this positive correlation is located spatially, and where negative correlated areas are. This can aid planners in understanding the synergies and tradeoffs between carbon sequestration and urban heat island mitigation when siting green infrastructure. For example, if the aim is to develop a green infrastructure project that provides both carbon sequestration and urban heat island mitigation, the following districts should be considered: most of Southeast Seattle, manufacturing and industrial district, and middle of Northwest Seattle.

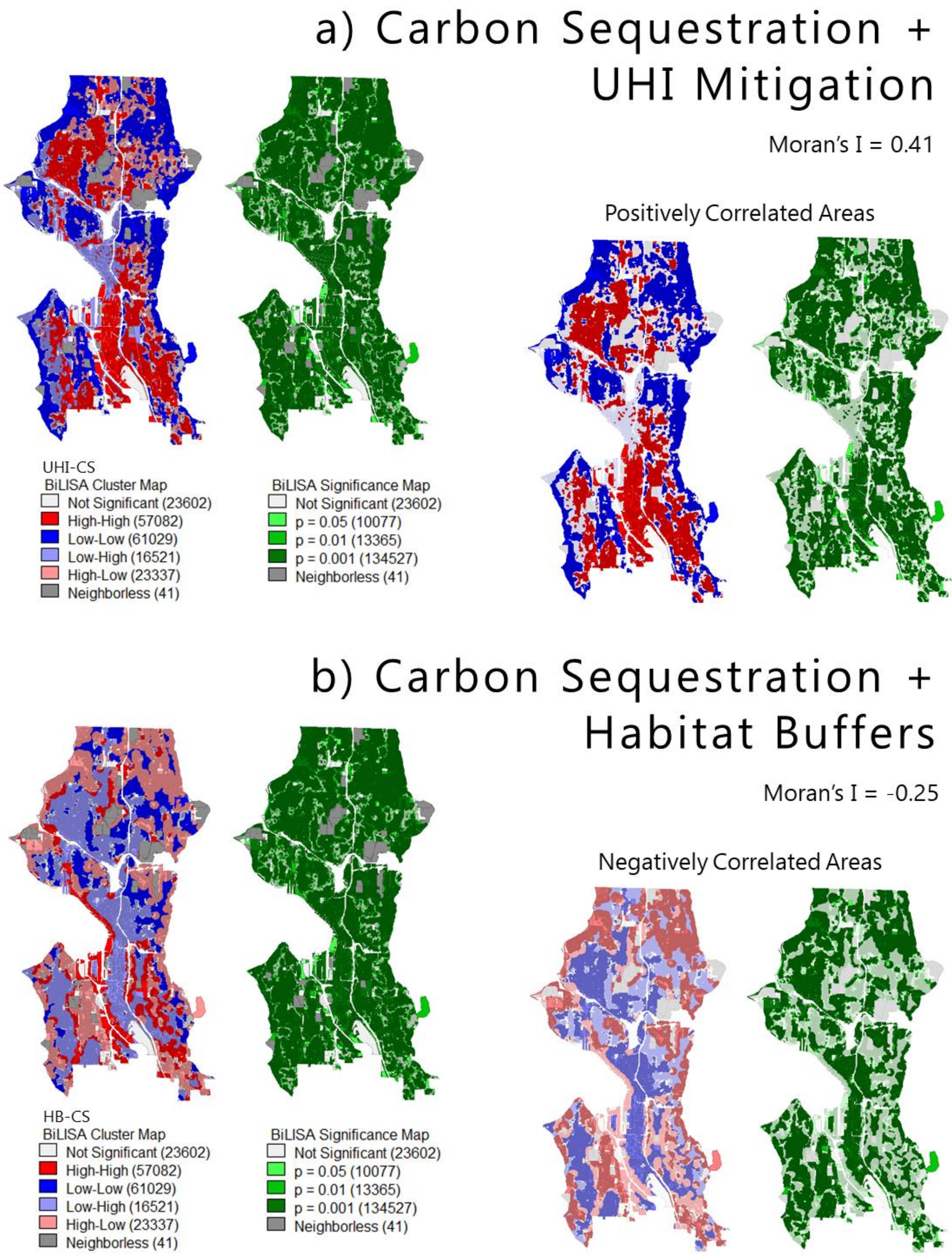

Figure 25: Bivariate Local Moran's I results from Geoda illustrating the spatial autocorrelation between ecosystem service pairs. a) Spatial correlation of UHI mitigation values and the surrounding carbon sequestration values. b) Spatial correlation of habitat buffer values and the surrounding carbon sequestration values.

Carbon Sequestration and Habitat Buffers (Negative Correlation)

I wanted to observe the effect of carbon sequestration need (which is linked to percent tree canopy cover) to need for habitat buffers at a central location. Therefore, the bivariate spatial correlation analyzed the correlation between need for habitat buffers and the spatial lag of carbon sequestration.

The Moran's I is -0.25 (Figure 25b), indicating that there is a high-low or low-high cluster relationship. Looking at Figure 25b, there are indeed more high-low or low-high spatial outliers than high-high or low-low spatial outliers. High-low areas indicate places of high need for habitat buffers but a low need for carbon sequestration, and vice versa for low-high areas. The significance map (Figure 25b) shows that the majority of the spatial outliers are significant at the 0.001 level. Additionally, the correlation in areas that are high-high or low-low spatial clusters are also significant at the 0.001 level.

These results support the findings from Band Collective Statistics where a relatively strong negative correlation (-0.35) was found between carbon sequestration and habitat buffers. However, the cluster map illustrates that even though there is an overall negative correlation there are also areas with a significant positive correlation. Nevertheless, this can also guide planners in understanding the synergies and tradeoffs between need for carbon sequestration and habitat buffers when siting green infrastructure. For example, if planners want to site green infrastructure to implement carbon sequestration policies or actions, they should expect that most of these areas (downtown Seattle, Northwest Seattle, or the industrial district) will not achieve goals to conserve fragmented habitats.

Summary

About 15% of land classified as high priority for each green infrastructure benefits need is publicly-owned. Additionally, 74% of publicly-owned land has at least 2 ecosystem service needs in agreement. This means that if green infrastructure is sited on publicly-owned land, 74% of the time green infrastructure would be addressing a need for at least 2 ecosystem services. This shows that there is opportunity to consolidate resources and improve efficiency in the siting of green infrastructure while making full use of its multifunctionality. It indicates a great starting point for collaboration between city departments to develop green infrastructure projects that are truly multifunctional. At the same time, since the two land uses with the largest area of land classified as high priority are residential and commercial, it is also crucial to continue educational and outreach efforts to residents and commercial business owners about greening their homes and offices.

Locations where interdepartmental green infrastructure projects can start focusing is listed below. These locations have been repeatedly highlighted as potential places with high priority for individual and multiple green infrastructure benefit needs.

- Southeast Seattle
- The Industrial District and manufacturing areas, Georgetown, Interbay
- North Seattle: middle of Lake City, middle of Northgate, east of Northwest, University District
- West Seattle: South of South Delridge and Roxhill
- Central area: Downtown

Understanding the tradeoffs and synergies between pairs of ES has the potential to help planners decide suitable GI locations where the highest benefit and service should be provided. The benefit of this is with different departments working to address various needs provided by

GI ecological services. Understanding synergies opens opportunities for interdepartmental partnership. It can decrease the cost for development of GI by increasing resources. For example, understanding that there is a positive correlation between carbon sequestration and urban heat island mitigation is an opportunity for the Parks and Recreation Department and Planning Department to pool their resources and produce results that are more effective.

CHAPTER 7 //

RECOMMENDATIONS AND CONCLUSIONS

OVERVIEW

Based on the results provided in Chapter 6, I provide several recommendations on the S-MCDA model regarding strengths, weaknesses and limitations. This chapter also provides policy and planning recommendations for the City of Seattle that aims to build interdepartmental collaboration in green infrastructure planning.

RECOMMENDATIONS

S-MCDA Model Recommendations

Strengths of the S-MCDA Model

- Publicly Available Data and Simple Methodology: This S-MCDA model is useful for planners who may not be experts in each of the ecosystem services field. It utilizes publicly available data and simple methodology to generate results that spark interdepartmental discussions on where green infrastructure can be sited to address multiple needs. It is recommended that this model be used as a pilot for incorporating the multiple benefits of green infrastructure into decision-making of related policies and plans.
- Dynamic Weighting of Ecosystem Services: The ability to easily adjust weights based on varying priorities presents an opportunity for using this model as a planning and outreach tool. For example, if departments convened for a meeting to determine how to weight different factors this model allows them to evaluate scenarios to inform their decision-meeting. Additionally, the model can be used during a public meeting where the community's feedback on which

ecosystem services are more important to them can be integrated on the fly into the model process.

- Querying of Final Results: A final output of this model includes a table with the land use, ownership, and priority level for each scenario by parcel. This table offers the potential to further analyze the results based on the different attributes. For example, if the City wants to identify all residential parcels with a high priority, this can be achieved through simple querying. This is useful if the City finds value in determining possible GI locations by land use type.

Weaknesses and Limitations of the S-MCDA Model

- Model Limitations: Despite the strengths of this model, there are many weaknesses and gaps that can be filled in future research. Chapter 4's S-MCDA literature review covered some of these weaknesses, and others were discovered during the analysis process. The following 5 points are areas for improvement in future research.

    1. **Weighted scenarios do not reflect actual priorities**: The weighted scenarios used in this model allowed for observing how priority areas shift when different ecosystem services are weighted higher than other benefits. However, these weighted scenarios do not reflect what the City of Seattle's current priorities are. Future research can include a study of what ecosystem services the City of Seattle and residents prioritize, and where priority areas are for green infrastructure based on that weighted scenario.

    2. **Multi-scale analyses to inform better green space planning**: A multi-scale model is more beneficial to target various levels of green space planning and decision-making. Spatial units used should be linked to the issue hand. For example, a fine scale helps illustrate ecosystem services for the immediate surrounding citizens. While a coarse spatial unit is easier to compare to socio-economic data that is accurate only at a

neighborhood scale, a scale where political action and support is more effective (Larondelle and Lauf 2016).

3. **Inclusion of green infrastructure physical land suitability analysis**: This model takes into account land use and ownership as the suitability factors for building green infrastructure. This was a suitable direction as this thesis defines green infrastructure to be any type of greenery in a city. However, if planners have a specific type of green infrastructure in mind, a second part of this model for future research should include physical land suitability requirements such as soil, distance from buildings, and slope.

4. **Identifying high priority ecosystem services in a specific location:** This model presented a map showing how many ecosystem services scored a high or medium-high priority in a specific location; however, this map does not show which ecosystem services scored a high or medium-high priority level. When planning for specific green infrastructure projects, knowing which ecosystem services are provided for can assist in interdepartmental collaboration. An interactive tool that produces these results can be a project for future research.

5. **Ecological fallacy in correlation analyses:** Band collection statistics in ArcGIS only looks at the correlation in values of overlying 30x30ft cells and does not provide any statistical significance. Ecological fallacy is a limitation to acknowledge when analyzing the results as using the same analysis at different spatial scales can produce different results. Additionally, the cluster analysis run in GeoDa analyzes the spatial correlation of a central value to surrounding values, rather than overlying values. The distance weights matrix used for this analysis is also subject to ecological fallacy as how a neighborhood is

defined can vary and affect the results. It is recommended that these limitations are clarified when presenting and using these results for decision making.

- Data Limitations: If the goal is to provide a first step to produce a rough estimate of high green infrastructure benefit areas, the current model with the data inputs serves that purpose. However, there are two ecosystem services whose data source and methodology could provide better insight on areas of need. By enhancing these two layers, we can expect to have results that are more representative of the current environmental conditions.
    1. **Stormwater Runoff Mitigation:** Stormwater runoff estimations would improve the results for areas needing runoff mitigation. Currently, the flow accumulation layer in the model does not include a type of storm event and soil infiltration; yet, these inputs are crucial to estimating stormwater runoff. Therefore, it is recommended that when the City of Seattle soil hydrological data is available on the USDA National Resources Conservation Service (NRCS) Web Soil Survey, a stormwater runoff estimation raster should be created and used for this model analysis. As stormwater runoff is a key issue that the City is working on, having the needs accurately represented is important for a multicriteria decision model to be effective.
    2. **Air Pollution Mitigation:** The use of buffers from roads and TRI facilities is a simple proxy to estimate air pollution needs when thorough research has been conducted on determining buffer distances. For a more accurate representation of air pollution concentrations, stronger research and studies need to be performed to collect air pollution data with large sample sizes across the whole city. With data that is suitable for interpolation, wind direction and speed can be another layer to incorporate into the interpolation of air pollution mitigation need.

Findings Based Recommendations for the City of Seattle

- Target Neighborhoods with Multiple ES in High Priority Agreement: It is evident that the industrial and manufacturing district ranks high among the land use categories in area of need for ecosystem services. However, the high ranking of industrial and manufacturing district compared to residential areas may cause concern for stakeholders worried that this will draw investment away from residential areas. Therefore, it is recommended that the City consider potential GI locations for industrial/manufacturing and residential land uses separately.

  From the weighted scenario analysis and areas of agreement analysis, it is recommended that the City of Seattle discuss the potential of siting green infrastructure in the following neighborhoods:

  - The Industrial and Manufacturing Districts
    - Adams in North Seattle
    - South Park
  - Residential areas:
    - Southeast Seattle: Corridor between Holly Park and Brighton
    - North Seattle: Middle of Northgate, Bitter Lake
  - Institutional or Public buildings:
    - University District in North Seattle offers an opportunity to site green infrastructure on public land that would provide multiple benefits.

- Encourage Interdepartmental Collaboration: Results showing area of land with more than 2 ecosystem services in agreement demonstrate an important opportunity for the City of Seattle to have interdepartmental collaboration when siting green infrastructure. By having departments collaborate on green infrastructure projects, this allows for resource pooling, thus increasing the possible budget for projects. As stated above, the use of a multi-criteria model can also be used to start a discussion between departments. The synergies and tradeoffs analysis also shows planners where to prioritize green infrastructure based on different ecosystem service priorities.

- Create Public-Private Partnerships: Using the multifunctionality of green infrastructure as a selling point for investing in green infrastructure can encourage cost effectiveness for green infrastructure projects on private land. A study found that stakeholders were effectively persuaded to contribute investments in green infrastructure sited on private land for cities that successfully publicized the multifunctionality of green infrastructure (Claro et al. 2013). An example is Portland, Oregon built $2.5 million of green infrastructure on privately owned land through a collaboration with Energy Trust Oregon (Claro et al. 2013). Portland was able to provide this funding through energy taxes which were highlighted to be used for green infrastructure that would reduce urban heat island temperatures (Claro et al. 2013).

  Therefore, public-private partnerships can be used to raise funding for specific use of green infrastructure, and acceptance to pay for green infrastructure projects can be bolstered by advertising the ecosystem services of green infrastructure. As mentioned before, the output of this model can be used for engagement and education purposes, which can also lead to more investment from private companies and residents.

- Incentivize Siting Green Infrastructure Projects in High Priority Areas: Various programs in Seattle encourage the development and maintenance of green infrastructure. For example, the ReLeaf program encourages urban forest stewardship among residents and involves them in increasing tree cover and maintaining existing trees (Green Cities Research Alliance 2012). Additionally, the RainWise Program provides rebates to residents living in a sewer overflow basin who install green stormwater infrastructure solutions, such as rain gardens (Seattle Public Utilities n.d.). Incentives for residents, property owners, and universities to install multifunctional green infrastructure projects can be built on existing programs that already encourage green infrastructure investment. If a resident, property owner, or university is in an area identified by the model as high priority, additional rebates or installation assistance can be provided as encouragement. Other assistance can come in the form of standard cost-effective designs available online, as well as a list of resources to help streamline the process of developing green infrastructure projects.

In addition, negotiating variances to the zoning codes can be a strategy to provide an incentive for developers to build a multifunctional green infrastructure. For example, if a developer is building in a high priority area and includes some form of green infrastructure, they could be allowed to build additional floor or increase their square footage.

Conclusion

The S-MCDA model built in this analysis offers the City of Seattle a way to understand how ecosystem services can add value to green infrastructure plans and develop stronger relationships with stakeholders while keeping social equity as a key factor in decision-making. The focus of green infrastructure may be on reducing CSOs and stormwater runoff but incorporating other ecological services of GI into the decision-making process can serve as an efficient way to address the goals and actions of various departments. I hope that this S-MCDA model serves as a platform to encourage interdepartmental collaboration and discussion about the future of green infrastructure planning in the City.

Appendix A // Methodology

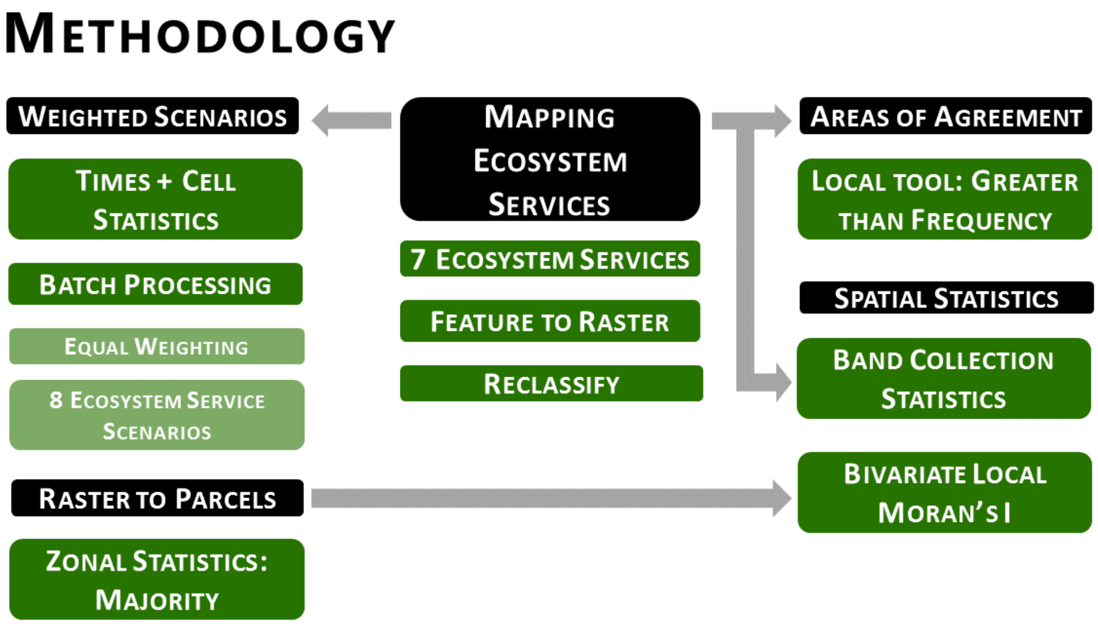

Figure 26: General workflow of the methodology.

Table 8: Summary of Reclassifications

Ecosystem Service	Metric	Priority = 1 (Low Need)	Priority = 5 (High Need)
Stormwater Runoff Mitigation	Flow Accumulation Buffers	> 100m	0 – 30m
Air Pollution Mitigation	Major Road Buffers	> 400m	0 – 50m
	TRI Air Pollution Site Kernel Density	Farthest quantile buffer from TRI site	Closest quantile buffer from TRI site
Carbon Sequestration	Carbon seq using % tree canopy cover equation	Highest carbon sequestration rates	Lowest carbon sequestration rates
Urban Heat Island Effect Mitigation	Land surface temperature	Lowest land surface temperatures	Highest land surface temperatures
Habitat Resilience	Buffers around environmentally critical areas	> 1300 ft	0 – 300ft
Access to Green Spaces	Walking distance + population density	Low pop density, within walking distance	High pop density, outside of walking dstance
Social Vulnerability	SoVI	Low social vulnerability based on SoVI	High social vulnerability based on SoVI

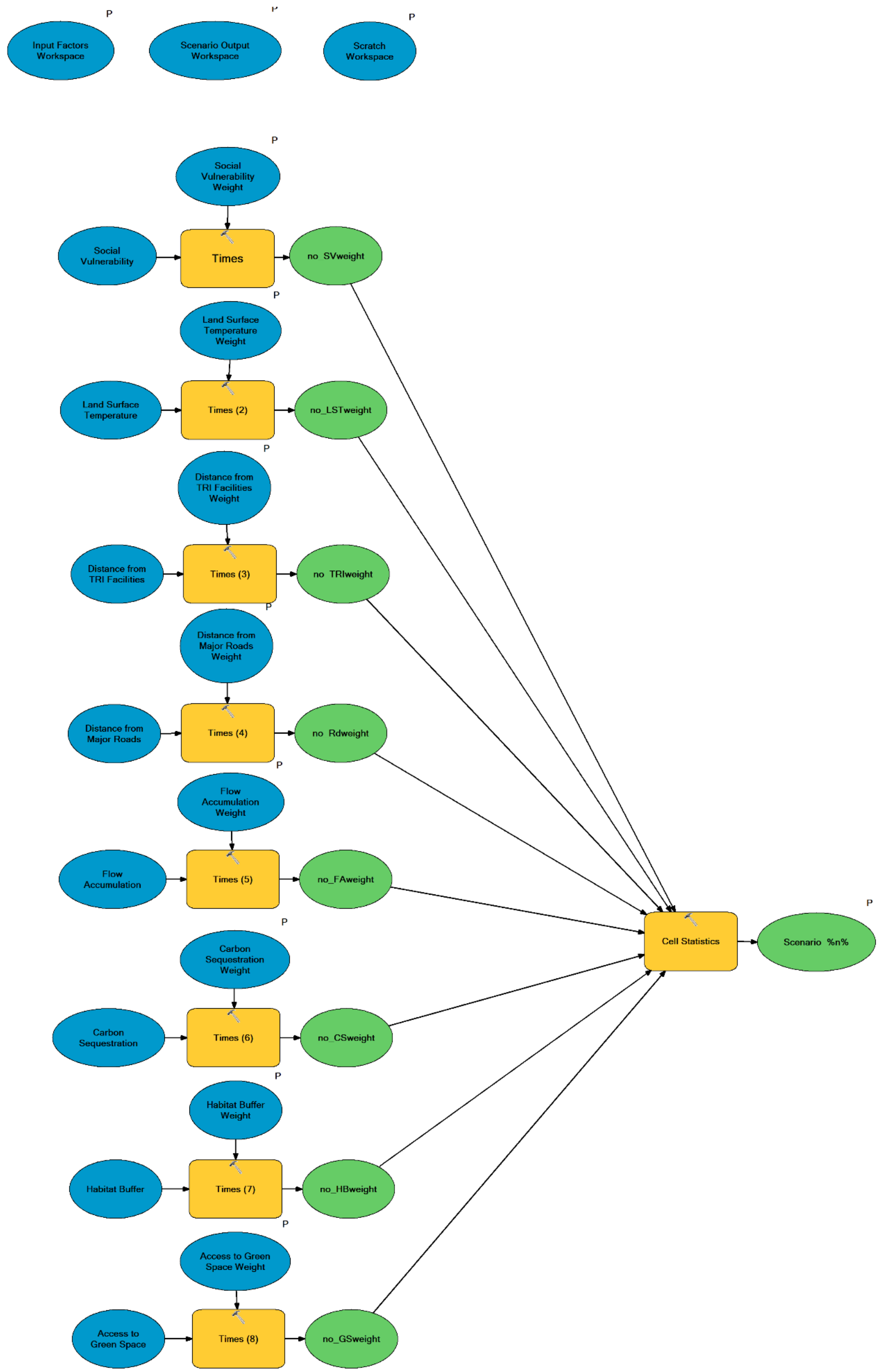

Figure 27: ModelBuilder tool for weighted scenarios.

Table 9: Weighting for the scenarios created in this analysis

	Weighted Scenarios								
Ecosystem Service	**Equal**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Flow Accumulation	0.125	**0.3**	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Air Pollution – Major Roads	0.125	0.1	**0.3**	0.1	0.1	0.1	0.1	0.1	0.1
Air Pollution – TRI	0.125	0.1	0.1	**0.3**	0.1	0.1	0.1	0.1	0.1
Carbon Sequestration	0.125	0.1	0.1	0.1	**0.3**	0.1	0.1	0.1	0.1
UHI Mitigation	0.125	0.1	0.1	0.1	0.1	**0.3**	0.1	0.1	0.1
Habitat Buffers	0.125	0.1	0.1	0.1	0.1	0.1	**0.3**	0.1	0.1
Access to Green Space	0.125	0.1	0.1	0.1	0.1	0.1	0.1	**0.3**	0.1
Social Vulnerability	0.125	0.1	0.1	0.1	0.1	0.1	0.1	0.1	**0.3**

References

100 Resilient Cities. 2016. "Seattle Resilience Workshop Workshop Report." Seattle. http://www.seattle.gov/Documents/Departments/Resilience/170120_100RC Seattle_Final Workshop Report.pdf.

Aflaki, Ardalan, Mahsan Mirnezhad, Amirhosein Ghaffarianhoseini, Ali Ghaffarianhoseini, Hossein Omrany, Zhi-Hua Wang, and Hashem Akbari. 2017. "Urban Heat Island Mitigation Strategies: A State-of-the-Art Review on Kuala Lumpur, Singapore and Hong Kong." *Cities* 62 (February). Pergamon:131–45. https://doi.org/10.1016/J.CITIES.2016.09.003.

Ahern, Jack. 2011. "From Fail-Safe to Safe-to-Fail: Sustainability and Resilience in the New Urban World." *Landscape and Urban Planning* 100 (4). Elsevier:341–43. https://doi.org/10.1016/J.LANDURBPLAN.2011.02.021.

———. 2013. "Urban Landscape Sustainability and Resilience: The Promise and Challenges of Integrating Ecology with Urban Planning and Design." *Landscape Ecology* 28 (6). Springer Netherlands:1203–12. https://doi.org/10.1007/s10980-012-9799-z.

Baur, Albert H., Steffen Lauf, Michael Förster, and Birgit Kleinschmit. 2015. "Estimating Greenhouse Gas Emissions of European Cities — Modeling Emissions with Only One Spatial and One Socioeconomic Variable." *Science of The Total Environment* 520 (July). Elsevier:49–58. https://doi.org/10.1016/J.SCITOTENV.2015.03.030.

Bolger, Douglas T., Andrew V. Suarez, Kevin R. Crooks, Scott A. Morrison, and Ted J. Case. 2000. "ARTHROPODS IN URBAN HABITAT FRAGMENTS IN SOUTHERN CALIFORNIA: AREA, AGE, AND EDGE EFFECTS." *Ecological Applications* 10 (4). Wiley-Blackwell:1230–48. https://doi.org/10.1890/1051-0761(2000)010[1230:AIUHFI]2.0.CO;2.

Bowler, Diana E, Lisette M Buyung-Ali, Teri M Knight, and Andrew S Pullin. 2010. "A Systematic Review of Evidence for the Added Benefits to Health of Exposure to Natural Environments." *BMC Public Health* 10 (1):456. https://doi.org/10.1186/1471-2458-10-456.

Brabec, Elizabeth, Stacey Schulte, and Paul L. Richards. 2002. "Impervious Surfaces and Water Quality: A Review of Current Literature and Its Implications for Watershed Planning." *Journal of Planning Literature* 16 (4). Sage PublicationsSage CA: Thousand Oaks, CA:499–514. https://doi.org/10.1177/088541202400903563.

Cardinale, Bradley J., J. Emmett Duffy, Andrew Gonzalez, David U. Hooper, Charles Perrings, Patrick Venail, Anita Narwani, et al. 2012. "Biodiversity Loss and Its Impact on Humanity." *Nature* 486 (7401). Nature Publishing Group:59–67. https://doi.org/10.1038/nature11148.

Census Bureau. 2010. "U.S. Census Bureau QuickFacts: Seattle City, Washington; UNITED STATES." 2010. https://www.census.gov/quickfacts/fact/table/seattlecitywashington,US/PST045217.

Chakhar, Salem, and Vincent Mousseau. 2008. "Spatial Multicriteria Decision Making." In *Encyclopedia* *of GIS*, edited by Shashi Shekhar and Hui Xiong, 747–53. https://doi.org/10.1007/978-0-387-35973-1_755.

Chicago, City of. 2014. "Green Stormwater Infrastructure Strategy." https://www.cityofchicago.org/content/dam/city/progs/env/ChicagoGreenStormwaterInfrastructureStrategy.pdf.

City of Chicago. n.d. "Chicago Climate Action." Accessed May 15, 2018. http://www.chicagoclimateaction.org/filebin/pdf/finalreport/Adaptation.pdf.

City of Seattle. 2017. "Moving the Needle: Environmental Progress Report." http://www.seattle.gov/Documents/Departments/OSE/Reports/MTN2.0_Final_Web.pdf.

Claro, Ashley, Theresa Formato, Samantha Huyhua, Robbie Lock, Kim Martineau, Andrea Moore, Petros Michaelides, et al. 2013. "Leveraging the Multiple Benefits of Green Infrastructure Sustainability Management Capstone Project for New York City's Department of Environmental Protection." http://sustainability.ei.columbia.edu/files/2014/02/Leveraging-CoBenefits-of-Green-Infrastructure-Fall-2013smallpdf-com.pdf.

Congress, 111th. 2009. *Clean Water Act*. House. https://www.congress.gov/bill/111th-congress/house-bill/4202.

Conservancy, The Nature. 2013. "The Case for Green Infrastructure," no. June:1–9.

Crossman, Neville D., Benjamin Burkhard, Louise Willemen, Ignacio Palomo, Evangelia G. Drakou, Berta Martín-Lopez, Timon McPhearson, et al. 2013. "A Blueprint for Mapping and Modelling Ecosystem Services." *Ecosystem Services* 4 (June). Elsevier:4–14. https://doi.org/10.1016/J.ECOSER.2013.02.001.

Cutter, Susan L. 1996. "Vulnerability to Environmental Hazards." *Progress in Human Geography* 20 (4). Sage PublicationsSage CA: Thousand Oaks, CA:529–39. https://doi.org/10.1177/030913259602000407.

Dobbs, Cynnamon, Francisco J. Escobedo, and Wayne C. Zipperer. 2011. "A Framework for Developing Urban Forest Ecosystem Services and Goods Indicators." *Landscape and Urban Planning* 99 (3–4):196–206. https://doi.org/10.1016/j.landurbplan.2010.11.004.

Droguett, Barbara Rodriguez. 2011. "Sustainability Assessment of Green Infrastructure Practices for Stormwater Management: A Comparative Energy Analysis."

GeoDa. n.d. "Global Spatial Autocorrelation (2)." Accessed May 30, 2018. http://geodacenter.github.io/workbook/5b_global_adv/lab5b.html.

Giordano, Lucilia do Carmo, and Paulina Setti Riedel. 2008. "Multi-Criteria Spatial Decision Analysis for Demarcation of Greenway: A Case Study of the City of Rio Claro, São Paulo, Brazil." *Landscape and Urban Planning* 84 (3–4):301–11. https://doi.org/10.1016/j.landurbplan.2007.09.006.

Green Cities Research Alliance. 2012. "Seattle's Forest Ecosystem Values: Analysis of the Structure, Function, and Economic Benefits." http://www.seattle.gov/trees/docs/Seattles_Forest_Ecosystem_Values_Report.pdf.

Grêt-Regamey, Adrienne, Enrico Celio, Thomas M. Klein, and Ulrike Wissen Hayek. 2013. "Understanding Ecosystem Services Trade-Offs with Interactive Procedural Modeling for Sustainable Urban Planning." *Landscape and Urban Planning* 109 (1):107–16. https://doi.org/10.1016/j.landurbplan.2012.10.011.

Gül, Atila, Abdullah Gezer, and Brian Kane. 2006. "Multi-Criteria Analysis for Locating New Urban Forests: An Example from Isparta, Turkey." *Urban Forestry and Urban Greening* 5 (2):57–71. https://doi.org/10.1016/j.ufug.2006.05.003.

Hansen, Rieke, and Stephan Pauleit. 2014. "From Multifunctionality to Multiple Ecosystem Services? A Conceptual Framework for Multifunctionality in Green Infrastructure Planning for Urban Areas." *Ambio* 43 (4):516–29. https://doi.org/10.1007/s13280-014-0510-2.

Hatt, Belinda E., Tim D. Fletcher, and Ana Deletic. 2009. "Hydrologic and Pollutant Removal Performance of Stormwater Biofiltration Systems at the Field Scale." *Journal of Hydrology* 365 (3–4). Elsevier:310–21. https://doi.org/10.1016/J.JHYDROL.2008.12.001.

Hazards & Vulnerability Research Institute, University of South Carolina. n.d. "SoVI® 2006-2010." Accessed March 20, 2018. http://artsandsciences.sc.edu/geog/hvri/sovi®-2006-2010.

Heynen, Nik. 2006. "Green Urban Political Ecologies: Toward a Better Understanding of Inner-City Environmental Change." *Environment and Planning A* 38 (3). SAGE PublicationsSage UK: London, England:499–516. https://doi.org/10.1068/a37365.

Hickey, M. Brian C., and Bruce Doran. 2004. "A Review of the Efficiency of Buffer Strips for the Maintenance and Enhancement of Riparian Ecosystems." *Water Quality Research Journal* 39 (3):311–17. https://doi.org/10.2166/wqrj.2004.042.

Holt, Alison R., Meghann Mears, Lorraine Maltby, and Philip Warren. 2015. "Understanding Spatial Patterns in the Production of Multiple Urban Ecosystem Services." *Ecosystem Services* 16. Elsevier:33–46. https://doi.org/10.1016/j.ecoser.2015.08.007.

Jerrett, Michael, Altaf Arain, Pavlos Kanaroglou, Bernardo Beckerman, Dimitri Potoglou, Talar Sahsuvaroglu, Jason Morrison, and Chris Giovis. 2004. "A Review and Evaluation of Intraurban Air Pollution Exposure Models." *Journal Of Exposure Analysis And Environmental Epidemiology* 15 (August). Nature Publishing Group:185. http://dx.doi.org/10.1038/sj.jea.7500388.

Kabisch, Nadja, Niki Frantzeskaki, Stephan Pauleit, Sandra Naumann, McKenna Davis, Martina Artmann, Dagmar Haase, et al. 2016. "Nature-Based Solutions to Climate Change Mitigation and Adaptation in Urban Areas: Perspectives on Indicators, Knowledge Gaps, Barriers, and Opportunities for Action." *Ecology and Society* 21 (2). The Resilience Alliance:art39. https://doi.org/10.5751/ES-08373-210239.

Kardinal Jusuf, Steve, N. H. Wong, Emlyn Hagen, Roni Anggoro, and Yan Hong. 2007a. "The Influence of

Land Use on the Urban Heat Island in Singapore." *Habitat International* 31 (2):232–42. https://doi.org/10.1016/j.habitatint.2007.02.006.

Kardinal Jusuf, Steve, N H Wong, Emlyn Hagen, Roni Anggoro, and Yan Hong. 2007b. "The Influence of Land Use on the Urban Heat Island in Singapore." *Habitat International* 31 (2):232–42. https://doi.org/https://doi.org/10.1016/j.habitatint.2007.02.006.

Karner, Alex A, Douglas S Eisinger, and Deb A Niemeier. 2010. "Near-Roadway Air Quality: Synthesizing the Findings from Real-World Data." *Environmental Science & Technology* 44 (14). American Chemical Society:5334–44. https://doi.org/10.1021/es100008x.

Kong, Fanhua, Haiwei Yin, Nobukazu Nakagoshi, and Yueguang Zong. 2010. "Urban Green Space Network Development for Biodiversity Conservation: Identification Based on Graph Theory and Gravity Modeling." *Landscape and Urban Planning* 95 (1–2). Elsevier:16–27. https://doi.org/10.1016/J.LANDURBPLAN.2009.11.001.

Kremer, Peleg, Zoé A. Hamstead, and Timon McPhearson. 2016. "The Value of Urban Ecosystem Services in New York City: A Spatially Explicit Multicriteria Analysis of Landscape Scale Valuation Scenarios." *Environmental Science & Policy* 62. Elsevier Ltd:57–68. https://doi.org/10.1016/j.envsci.2016.04.012.

Kuo, Frances E., and William C. Sullivan. 2001. "Environment and Crime in the Inner City." *Environment and Behavior* 33 (3). Sage PublicationsSage CA: Thousand Oaks, CA:343–67. https://doi.org/10.1177/0013916501333002.

Larondelle, Neele, and Steffen Lauf. 2016. "Balancing Demand and Supply of Multiple Urban Ecosystem Services on Different Spatial Scales." *Ecosystem Services* 22. Elsevier:18–31. https://doi.org/10.1016/j.ecoser.2016.09.008.

Lennon, Mick. 2015. "Green Infrastructure and Planning Policy: A Critical Assessment." *Local Environment* 20 (8). Taylor & Francis:957–80. https://doi.org/10.1080/13549839.2014.880411.

Lo, Alex Y., Jason A. Byrne, and C. Y. Jim. 2017. "How Climate Change Perception Is Reshaping Attitudes towards the Functional Benefits of Urban Trees and Green Space: Lessons from Hong Kong." *Urban Forestry and Urban Greening* 23. Elsevier GmbH.:74–83. https://doi.org/10.1016/j.ufug.2017.03.007.

Lovasi, G S, J W Quinn, K M Neckerman, M S Perzanowski, and A Rundle. 2008. "Children Living in Areas with More Street Trees Have Lower Prevalence of Asthma." *Journal of Epidemiology and Community Health* 62 (7). BMJ Publishing Group Ltd:647–49. https://doi.org/10.1136/jech.2007.071894.

Maantay, Juliana. 2007. "Asthma and Air Pollution in the Bronx: Methodological and Data Considerations in Using GIS for Environmental Justice and Health Research." *Health & Place* 13 (1):32–56. https://doi.org/10.1016/j.healthplace.2005.09.009.

Madureira, Helena, and Teresa Andresen. 2014. "Planning for Multifunctional Urban Green

Infrastructures: Promises and Challenges." *URBAN DESIGN International* 19 (1). Nature Publishing Group:38–49. https://doi.org/10.1057/udi.2013.11.

Malczewski, Jacek. 2004. "GIS-Based Land-Use Suitability Analysis: A Critical Overview." *Progress in Planning* 62 (1):3–65. https://doi.org/10.1016/j.progress.2003.09.002.

———. 2006. "GIS-Based Multicriteria Decision Analysis: A Survey of the Literature." *International Journal of Geographical Information Science* 20 (7):703–26. https://doi.org/10.1080/13658810600661508.

Martinez-Alier, Joan, Giuseppe Munda, and John O'Neill. 1998. "Weak Comparability of Values as a Foundation for Ecological Economics." *Ecological Economics* 26 (3). Elsevier:277–86. https://doi.org/10.1016/S0921-8009(97)00120-1.

McPhearson, Timon, Peleg Kremer, and Zoé A. Hamstead. 2013. "Mapping Ecosystem Services in New York City: Applying a Social-Ecological Approach in Urban Vacant Land." *Ecosystem Services* 5 (September). Elsevier:11–26. https://doi.org/10.1016/j.ecoser.2013.06.005.

McPherson, E Gregory, David Nowak, Gordon Heisler, Sue Grimmond, Catherine Souch, Rich Grant, and Rowan Rowntree. 1997. "Quantifying Urban Forest Structure, Function, and Value: The Chicago Urban Forest Climate Project." *Urban Ecosystems* 1 (1):49–61. https://doi.org/10.1023/A:1014350822458.

Meerow, Sara, and Joshua P. Newell. 2017. "Spatial Planning for Multifunctional Green Infrastructure: Growing Resilience in Detroit." *Landscape and Urban Planning* 159 (Supplement C). Elsevier B.V.:62–75. https://doi.org/10.1016/j.landurbplan.2016.10.005.

Mikati, Ihab, Adam F Benson, Thomas J Luben, Jason D Sacks, and Jennifer Richmond-Bryant. 2018. "Disparities in Distribution of Particulate Matter Emission Sources by Race and Poverty Status." *American Journal of Public Health* 108 (4). American Public Health Association:480–85. https://doi.org/10.2105/AJPH.2017.304297.

Muscutt, A D, G L Harris, S W Bailey, and D B Davies. 1993. "Buffer Zones to Improve Water Quality: A Review of Their Potential Use in UK Agriculture." *Agriculture, Ecosystems & Environment* 45 (1):59–77. https://doi.org/https://doi.org/10.1016/0167-8809(93)90059-X.

NOAA. n.d. "Social Vulnerability Index." Accessed March 20, 2018. https://coast.noaa.gov/arcgis/rest/services/sovi/sovi_tracts2010/MapServer.

NYCEP. n.d. "NYC Green Infrastructure Program." http://www.nyc.gov/html/dep/html/stormwater/using_green_infra_to_manage_stormwater.shtml.

Office of Planning & Community Development. 2015. "Seattle Comprehensive Plan." 2015. http://www.seattle.gov/opcd/ongoing-initiatives/comprehensive-plan.

Office of Sustainability and Environment. 2017. "Preparing for Climate Change."

https://www.seattle.gov/Documents/Departments/Environment/ClimateChange/SEAClimatePreparedness_August2017.pdf.

———. 2018. “Seattle Resilience Strategy.” 2018. http://www.seattle.gov/resilience/strategy.

Peterjohn, William T., and David L. Correll. 1984. “Nutrient Dynamics in an Agricultural Watershed: Observations on the Role of A Riparian Forest.” *Ecology* 65 (5). WileyEcological Society of America:1466–75. https://doi.org/10.2307/1939127.

Philadelphia Water Department. n.d. “Adaptation, Mitigation, City Greening and Water Cleaning – Philadelphia Water Tackles Climate Change.” Accessed May 15, 2018a. http://www.phillywatersheds.org/adaptation-mitigation-city-greening-and-water-cleaning-–-philadelphia-water-tackles-climate-change.

———. n.d. “Green City, Clean Waters.” Accessed May 15, 2018b. http://www.phillywatersheds.org/what_were_doing/documents_and_data/cso_long_term_control_plan.

———. n.d. “Green Stormwater Infrastructure.” Accessed May 15, 2018c. http://www.phillywatersheds.org/what_were_doing/green_infrastructure.

Pickett, S. T. A., and M. L. Cadenasso. 2007. “Linking Ecological and Built Components of Urban Mosaics: An Open Cycle of Ecological Design.” *Journal of Ecology* 0 (0). Wiley/Blackwell (10.1111):071029080921001–??? https://doi.org/10.1111/j.1365-2745.2007.01310.x.

Priego, C., J.-H. Breuste, and J. Rojas. 2008. “Perception and Value of Nature in Urban Landscapes: A Comparative Analysis of Cities in Germany, Chile and Spain.” *Landscape Online*. https://doi.org/10.3097/LO.200807.

Pugh, Thomas A. M., A. Robert MacKenzie, J. Duncan Whyatt, and C. Nicholas Hewitt. 2012. “Effectiveness of Green Infrastructure for Improvement of Air Quality in Urban Street Canyons.” *Environmental Science & Technology* 46 (14). American Chemical Society:7692–99. https://doi.org/10.1021/es300826w.

Raymond, Crystal. 2016. “Seattle City Light Climate Change Vulnerability Assessment and Adaptation Plan Executive Summary Goals and Objectives.” https://www.seattle.gov/light/enviro/docs/Seattle_City_Light_Climate_Change_Vulnerability_Assessment_and_Adaptation_Plan.pdf.

Rosa, Daniele La, Luca Barbarossa, Riccardo Privitera, and Francesco Martinico. 2014. “Agriculture and the City: A Method for Sustainable Planning of New Forms of Agriculture in Urban Contexts.” *Land Use Policy* 41 (November). Elsevier Ltd:290–303. https://doi.org/10.1016/j.landusepol.2014.06.014.

Roth, Matthias, and Winston T.L. Chow. 2012. “A Historical Review and Assessment of Urban Heat Island Research in Singapore.” *Singapore Journal of Tropical Geography* 33 (3):381–97. https://doi.org/10.1111/sjtg.12003.

Rowntree, Rowan A., and David J. Nowak. 1991. “Quantifying the Role of Urban Forests in Removing Atmospheric Carbon Dioxide.” *Journal of Arboriculture. 17(10): 269-275.* 17 (10). https://www.fs.usda.gov/treesearch/pubs/18726.

Scherer, D., U. Fehrenbach, T. Lakes, S. Lauf, F. Meier, and Schuster C. 2013. “Quantification of Heat-Stress Related Mortality Hazard, Vulnerability and Risk in Berlin, Germany.” *Erde* 144 (3–4):238–59. https://doi.org/10.12854/erde-144-17.

Seattle Public Utilities. n.d. “RainWise Program.” Accessed June 10, 2018. http://www.seattle.gov/util/EnvironmentConservation/Projects/GreenStormwaterInfrastructure/RainWise/index.htm.

———. 2009. “2010 CSO Reduction Plan Amendment.” Seattle. http://www.seattle.gov/util/cs/groups/public/@spu/@usm/documents/webcontent/02_008056.pdf.

———. 2017. “Wastewater Collection System: 2016 Annual Report.” https://www.seattle.gov/util/cs/groups/public/@spu/@drainsew/documents/webcontent/1_060955.pdf.

Sweeney, Bernard W., and J. Denis Newbold. 2014. “Streamside Forest Buffer Width Needed to Protect Stream Water Quality, Habitat, and Organisms: A Literature Review.” *Journal of the American Water Resources Association* 50 (3):560–84. https://doi.org/10.1111/jawr.12203.

Tzoulas, Konstantinos, Kalevi Korpela, Stephen Venn, Vesa Yli-Pelkonen, Aleksandra Kamierczak, Jari Niemela, and Philip James. 2007. “Promoting Ecosystem and Human Health in Urban Areas Using Green Infrastructure: A Literature Review.” *Landscape and Urban Planning* 81:167–78. https://doi.org/10.1016/j.landurbplan.2007.02.001.

University of South Carolina. n.d. “2006-2010 Social Vulnerability Component Summary.” Accessed March 20, 2018. http://artsandsciences.sc.edu/geog/hvri/sites/sc.edu.geog.hvri/files/attachments/sovi0610_factorsb.pdf.

USDA-NRCS. 1986. “Urban Hydrology for Small Watersheds.” https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf.

USEPA. n.d. “Chicago, IL Uses Green Infrastructure to Reduce Extreme Heat.” Accessed May 15, 2018a. https://www.epa.gov/arc-x/chicago-il-uses-green-infrastructure-reduce-extreme-heat.

———. n.d. “What Is Green Infrastructure.” Accessed May 1, 2018b. https://www.epa.gov/green-infrastructure/what-green-infrastructure.

———. 2009. “Managing Wet Weather with Green Infrastructure Green Jobs Training A Catalog of Training Opportunities for Green Infrastructure Technologies.” www.epa.gov/greeninfrastructure.

Washington State Department of Ecology. 2012. “Stormwater Management Manual for Western

Washington Volume I Minimum Technical Requirements and Site Planning." https://fortress.wa.gov/ecy/publications/parts/1210030part2.pdf.

Weng, Q. 2001. "A Remote Sensing?GIS Evaluation of Urban Expansion and Its Impact on Surface Temperature in the Zhujiang Delta, China." *International Journal of Remote Sensing* 22 (10):1999–2014. https://doi.org/10.1080/713860788.

Whitford, V., A.R. Ennos, and J.F. Handley. 2001. "'City Form and Natural Process'—indicators for the Ecological Performance of Urban Areas and Their Application to Merseyside, UK." *Landscape and Urban Planning* 57 (2). Elsevier:91–103. https://doi.org/10.1016/S0169-2046(01)00192-X.

Wolch, Jennifer R., Jason Byrne, and Joshua P. Newell. 2014. "Urban Green Space, Public Health, and Environmental Justice: The Challenge of Making Cities 'Just Green Enough.'" *Landscape and Urban Planning* 125. Elsevier B.V.:234–44. https://doi.org/10.1016/j.landurbplan.2014.01.017.

Wong, David W, Lester Yuan, and Susan A Perlin. 2004. "Comparison of Spatial Interpolation Methods for the Estimation of Air Quality Data." *Journal of Exposure Analysis and Environmental Epidemiology* 14:404–15. https://doi.org/10.1038/sj.jea.7500338.

World Health Organization. 2018a. "Air Pollution." World Health Organization. 2018. http://www.who.int/airpollution/en/.

———. 2018b. "Ambient Air Pollution: Health Impacts." World Health Organization. 2018. http://www.who.int/airpollution/ambient/health-impacts/en/.

———. 2018c. "WHO Global Ambient Air Quality Database (Update 2018)." World Health Organization. 2018. http://www.who.int/airpollution/data/cities/en/.

Xu, Hanqiu. 2007. "Extraction of Urban Built-up Land Features from Landsat Imagery Using a Thematic-Oriented Index Combination Technique." *Photogrammetric Engineering and Remote Sensing* 73 (12):1381–91. https://doi.org/10.14358/PERS.73.12.1381.

Younger, Margalit, Heather R Morrow-Almeida, Stephen M Vindigni, and Andrew L Dannenberg. 2008. "The Built Environment, Climate Change, and Health Opportunities for Co-Benefits." *Am J Prev Med Elsevier Inc. on Behalf of American Journal of Preventive Medicine* 35 (5):517–26. https://doi.org/10.1016/j.amepre.2008.08.017.

Zhu, Yifang, William C Hinds, Seongheon Kim, and Constantinos Sioutas. 2002. "Concentration and Size Distribution of Ultrafine Particles Near a Major Highway." *Journal of the Air & Waste Management Association* 52 (9). Taylor & Francis:1032–42. https://doi.org/10.1080/10473289.2002.10470842.

Zucca, Antonella, Ali M. Sharifi, and Andrea G. Fabbri. 2008. "Application of Spatial Multi-Criteria Analysis to Site Selection for a Local Park: A Case Study in the Bergamo Province, Italy." *Journal of Environmental Management* 88 (4):752–69. https://doi.org/10.1016/j.jenvman.2007.04.026.