GREEN ROOF ADOPTION: A GIS-INTEGRATED COST-BENEFIT ANALYSIS IN ATLANTA INCORPORATING A POSITIVE EXTERNALITY

by

MADHUR LAMSAL

(Under the Direction of **Jeffrey D. Mullen**)

This research draws on three previous studies that have quantified the costs and benefits associated with conventional roofs versus green roofs. Using those studies as alternative paramerterizations, we estimate from a private and public perspective the costs and benefits associated with installing and maintaining an extensive green roof in the city of Atlanta. In addition, this study also quantifies the health care costs borne from coal-fired power plants. Geographic Information System (GIS) is used to spatially identify the privately and socially optimal roof type for each building. The research also explores the effect of a positive externality (ambient air cooling from green roof adoption) on the optimal roof type.

INDEX WORDS: Green Rooftops, Urban Heat Island Effect, Stormwater Runoff, Air Quality, Health Care Cost, Externality, and Subsidies

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by

B.S., The University of Michigan, 2008

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment

of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2012

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August 2012

DEDICATION

To my father Mr. Nanda Ram Lamsal, and family

ACKNOWLEDGEMENTS

I would like to thank Jeff Mullen for his support and guidance as my major advisor. I am also grateful for the time and effort of my committee members Greg Colson and Susana Ferreira. In addition, I would like to acknowledge Liz Kramer for her invaluable insights into the interdisciplinary aspects of my research. I owe a great deal of thanks to Steve William for providing GIS data.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

CHAPTER 1

INTRODUCTION

1.1 Background: Problem with Modern Urban Landscapes

As the nomadic nature of human beings came to an end with the invention of agriculture, people started to settle, where natural resources were abundant such as fresh water, alluvial soil, and woodland. Human population began to coalesce into towns and cities. Urbanization is defined as "the development of land into residential, commercial, and industrial properties, much of which is in the form of impervious surfaces. Urban and suburban developments cause profound changes to natural conditions by altering the terrain, modifying the vegetation, air quality, temperature and soil characteristics, and introducing pavement, buildings, and drainage infrastructure" (Booth, 1991). The natural environment is continuously losing its pristine and unaltered cycle. For example, natural surfaces such as soil act as a natural drainage system to absorb most precipitation, but rapid urbanization has reduced the porous surface as well as natural vegetation in many cities. Therefore, as a result, cities confront urban floods. Similarly, trees and other natural vegetation absorb heat and cast shade on their surroundings that cools an area in daytime. Due to the lack of vegetation, urbanized areas remains hotter than its surrounding rural area. The consequences of urbanization have lead to poor air quality, higher health care costs, and localized higher temperatures than surrounding rural areas, higher energy demand, and higher costs for stormwater management (United Nations, 2011). The effect of urbanization on the private as well as societal level is discussed below.

1.2 Urban Heat Island

Observed temperatures in city areas are generally higher than surrounding rural areas, a phenomenon known as the urban heat island effect (UHIE). Impervious surfaces and material used in urban structures store heat in daytime and reradiate it at night causing the city temperature to remain higher than its surrounding areas (Oke, 1982). Urban temperatures during summer afternoons in the U.S. have increased 2 to 4^0F during the last 40 years (Akbari, et al., 1992). The UHIE is a well-observed phenomena in Atlanta, Georgia (Zhou and Shepherd, 2010). Likewise, the UHIE is enhanced by other factors as well, such as heat released from vehicles, power plants, air conditioners, and other heat sources (Rizwan, et al., 2008). Within the complex environment of the city, heat islands can also exacerbate the impact of heat waves. Anthropogenic heat with vehicular and industrial emissions can further intensify the UHIE by creating an inversion layer, resulting in increases in air conditioning demand (Rosenfeld, et al., 1995) .

1.3 Increased Energy Demand and Power Plant Emission

Various studies have conducted to calculate the correlation between the urban heat island effect and energy consumption. The city of Atlanta is a growing with a population 420,003 (U.S. Department of Commerce, Census Bureau, 2012). For cities with populations larger than 100,000 the peak electricity load has increased 1.5-2 % for every 1^0F increase in temperature (Akbari, et al., 1992). The urban heat island effect is responsible for 5-10 % of peak electricity demand for cooling in cities (U.S. Environmental Protection Agency, 2008). Increased demand for electricity directly relates to additional operation hours of power plants. Coal is the major electricity generating fuel in the state of Georgia. According to Georgia Power, which provides the majority of electricity in the greater Atlanta area, 62% of energy produced in Georgia comes from coal-fired power plants (Georgia Power, 2011). Additional operational hours of coal-fired power plants relate to increased emission of pollutants in the surrounding sky of the city. eGRID (Emissions & Generation Resource Integrated Database) developed and maintained by the U.S. EPA (Environmental Protection Agency), keeps the record of emission rates of the pollutants per kilowatt energy produced.

1.4 Stormwater Retention and Water Quality

Stormwater runoff management is another major problem in cities. Storm water runoff is precipitation that runs over the ground. The lack of porous surface forces the storm water to make its own course during heavy precipitation events, creating urban flooding (Hathaway, et al., 2008). Impervious cover decreases the amount of rainwater that can naturally infiltrate into the soil, and increases the volume and rate of stormwater runoff (Moran, et al., 2004). This gives rise to more frequent and severe flooding, and therefore greater potential damage to public and private property. Many cities charge stormwater fees to the citizenry based on areas of impervious surface relative to the total property surface area. In addition to the consequences of impervious surfaces for flooding and property damage, there are significant environmental effects for surrounding bodies of water. When the rain falls on impervious surfaces, it makes its own course picking up pollutants along the way and finally dumping pollutants into a pond or nearby navigable water bodies. Most cities in the U.S. do not allow direct discharging of pollutants into navigable water bodies. They are required to clean organic and suspended particles to limit pollution to the environment. The Georgia Water Quality Control Act was passed in 2006 to restore and maintain water purity and supplies within the state and require reasonable treatment of sewage, industrial water, and other waste prior to their discharge into the waters of the state under the National Pollutant Discharge Elimination System (NPDES) (Georgia Secretary of State, 2012).

1.5 Air Pollution and Health Care

Another major effect of urbanization is the degradation of air quality due to the reduction of natural vegetation and trees. Different means of transportation, industrial smoke, dust, and liquid droplets from fuel combustion produce suspended particulate matter in the air-shed of a city (Brown, 1997). The EPA has identified and set standards for six pollutants (sulphur dioxide, nitrogen oxide, carbon monoxide, ozone, particulate matter, and lead) as per National Ambient Air Quality Standards (NAAQS) under the Clean Air Act of 1970 (U.S. Environmental Protection Agency 2011g). The Atlanta region has not met the federal ground-level ozone standards in any year since 1980 (U.S. Environmental Protection Agency, 2012). More than half of metro Atlanta’s ozone comes from vehicle emissions. Therefore, the city of Atlanta classified as it has failed to meet NAAQS.

Muller, et al. (2006) found that urban emissions constitute 52% of total emissions of the above-mentioned six-pollutants in the United States. Anthropogenic heat and pollution can further intensify the UHIE by creating an inversion layer, resulting in increased heat stress related mortality and illness (Hogrefe, et al., 2004). Sensitive populations such as the elderly and children are more vulnerable than young adults under the influence of a heat wave. The Centers for Disease Control and Prevention (2006) estimated that from 1979-2003, excessive heat exposure contributed to more than 8000 premature deaths in the United States (Center for Disease Control and Prevention, 2006). With vehicular and power plant emissions, the reactive chemistry in urban areas can be greatly affected by nitrogen oxide (NO_x), which can cause respiratory diseases and increase the risk of heart attacks (Brunekreef and Holgate, 2002).

1.6 Stresses on Utility Infrastructure

The United Nations (2011) states that urbanization increases the stress on private and public utilities, resulting in an increased demand for energy, water, sewer service, and transportation. The residential and commercial sector make up 38% of total annual energy consumption in the U.S. (Heiple and Sailor, 2008). For example, the UHIE intensifies the air conditioning demand and to meet increased energy demand, more than 150 new coal-fired power plants are proposed in the U.S. alone by 2030 (Clark, et al., 2008).

The rapid change of green space into urban structures such as shopping malls and neighborhoods increases the need for sewer system infrastructure, which requires billions of dollars in initial investment. For the city of Atlanta, stormwater infrastructure costs and operation and maintenance are estimated to be \$3.2 billion - \$5.5 billion from 2010-2030 (Bluestone, 2010).

1.7 External versus Private Costs

To offset the costs of managing stormwater flows exacerbated by extensive areas covered by impervious surfaces, local governments charge stormwater and sewer fees to residential, industrial, and commercial enterprises. The fees charged are typically based on the area of impervious surface covering a particular property. The property owners (or their tenants) realize these fees directly. As such, they are taken into account when the owner makes private decisions about selling, leasing, or making physical changes to a property. In other words, the stormwater fee associated with a property is a private cost. Many cities such as Portland, Oregon, and Ann Arbor, Michigan and Gwinnet, County, Georgia charge stormwater fees for impervious areas. Another private cost associated with a property is the cost of cooling the building. As an urban area expands, the UHIE often intensifies. As such, a new structure will realize its own private cooling costs while simultaneously increasing the cooling costs of its neighbors. This represents a classic economic externality where the costs of one building owner's actions are not fully internalized. The increase in the cooling costs of one due to the actions of another is an example of an economic externality. Thus, economic externality refers to a situation in which one's activity costs or benefits others while ignoring the responsibility of that cost or benefit.

Other externalities associated with urbanization are related to human health. The degradation of air quality in an urban area due to polluting activities is exacerbated by the replacement of vegetative cover with impervious surfaces. Poor air quality has been reported as one of the primary reason for the respiratory problems among city dwellers (Brown, 1997;World Health Organization,2011). Muller, et al. (2006) quantified the gross annual damage of six pollutants (particulate $matter_{10, 2.5}$, ammonia, sulphur dioxide, nitrogen oxides and volatile organic compounds) as varying between $71 billion and $277 billion in the U.S.

The UHIE of large urban areas increase the risk of heat-related illness among city dwellers (Blum, et al., 1998). Semenza, et al. (1999) found that during the July 1995 heat wave in Chicago, the majority of excess hospital admissions were due to dehydration, heat stroke, and heat exhaustion among people with underlying medical conditions. The health care cost associated with heat-related illness has been increasing among cities where the UHIE has become a common phenomenon in summer, such as Atlanta, Georgia. Additional expenditure on health care is an external cost imposed upon people due to the UHIE. The USEPA has reported that principle greenhouse gases that enter the atmosphere because of human activities are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_x) and fluorinated gases. The ambient air temperature and quality is influenced by human activities because greenhouse gases trap heat in the atmosphere and increase the temperature of large areas.

1.8 Ability of Green Roofs to address Consequences of Urbanization

Green roof technology has been proposed to mitigate the effects of the UHIE, stormwater runoff, and air quality degradation. A wide range of literature has been published analyzing these effects (Acks, 2006, Banting, et al., 2005, Clark, et al., 2008, Liptan, 2003), and big cities like Chicago and New York have been promoting and adopting green roofs as a mitigation tool.

1.8.1 Urban Heat Island Mitigation

Liptan (2003) stated that according to the preliminary calculation by the Portland Bureau of Environmental Services, greening 100% of rooftops in one commercial or industrial neighborhood could reduce that neighborhood's heat island by 50-90%. Recently two of the research centers, one in Chicago and the other in Florida, have compared surface temperatures between green and conventional roofs, and observed that green roof surface temperature was 48^{o}F cooler than the surface temperature of the conventional roof, and also noted that the near surface temperature above the green roof was about 7^{0}F cooler than that over the conventional roof (Cummings, et al., 2007;U.S. Department of Energy,2011). A study in New York City modeled air temperature reduction two meters (6.5 feet) above the roof surface based on a scenario assuming 100 percent conversion of all available roofs to green roofs. This model results estimated a temperature reduction of above 0.4^0F, averaged for the city as a whole, averaged over all times of the day (Rosenzweig, et al., 2006). However, reduction of the urban heat island effect, and its associated externalities, is likely to require a fairly wide spread implementation of green roofs. Localized and sporadic implementation of green roofs may not result in significant reductions in the UHIE (Banting, et al., 2005).

1.8.2 Green Space and Microclimatic Effect

Academics, researchers, and policy makers have been investigating the impact of vegetation in the urban environment. It has been frequently iterated in research publications that the ambient air in and around the boundary of a green space differs from its urban surroundings, creating a unique microclimatic zone within a larger climate zone.

1.8.3 Park and Microclimate

Field research performed in Tama, New Town, a city in the west of the Tokyo metropolitan area, Japan, found that, at noon, a 0.6 km^2 park can reduce the air temperature by up to 2.7^0F in a busy commercial area 1 km downwind (Ca, et al., 1998). Saito et al. (1991) noted that a small green area with broad green-leaved trees of 2400 m^2 can cool an area about 20m from the green space, with the cooled area moving according to the wind direction. A simulation study of the thermal effect of green spaces on their surrounding areas has revealed that smaller green areas with sufficient intervals (200 m) are preferable for effectively the cooling surrounding areas (Honjo and Takakura, 1991). An additional study carried out as a part of the work of the European Union funded-Joule Project “PRECis: assessing the potential for renewable energy in cities" concluded that a 1 Kelvin[1] reduction in ambient air temperature is to be expected for a 100 m^2 increase of the ratio of green to build area, for the urban texture under consideration (Dimoudi and Nikolopoulou, 2003).

1.8.4 Green Roof, Green Wall and Microclimate

The creation of microclimates due to green space may differ depending on plant variety, however, in comparison with asphalt surface, even stand-alone grass-covered green space temperatures have been found to be about 0.18 ^{0}F lower (Takebayashi and Moriyama, 2009). Depending upon the adoption percentage over available flat roof surface, green roofs can cool ambient air right above it up to 2 meters (Rosenfeld, et al., 1995). The leeward side always has the lowest air temperature. To examine the thermal effect of green roof and green walls in a build environment, Alexandari, et al. (2006) simulated a micro-scale model in nine cities (London (UK), Montreal (Canada), Moscow (Russia), Athens (Greece), Beijing (China), Riyadh (Saudi Arabia), Hong Kong (China), Mumbai (India), Brasilia (Brazil)) around the world. The research found that humid climate cities such as Hong Kong and can benefit most from green surfaces, especially with both roofs and walls covered with vegetation, reaching up to 15.12 ^{0} F maximum temperature decrease for humid Hong Kong. Regarding the urban geometry, the wider a canyon (5-15m) is , the weaker the effect of green roofs and green walls on temperature reductions (Alexandri and Jones, 2008).

1.8.5 Green Space and Energy Demand

[1] Kelvin degree has the same magnitude as Celsius degree.

Ca et al. (1998) have estimated, at an individual level, a four storey building can save up to 15% of cooling electricity load because of proximity to a park of 0.6 km^2, saving 4000 kWh of cooling load electricity within one hour from 1 to 2 p.m. on a hot summer day toward the leeward of the study area, Tokyo, Japan. If green roofs and green walls are applied appropriately, cooling energy can be saved by 32- 100% in cities of humid climates (Alexandri and Jones, 2008).

1.8.6 Stormwater Management, Retention, and Water Quality

Plants and growing mediums of green roofs absorb water that would otherwise become runoff. Research conducted in North Carolina showed that a green roof can retain up to 100% of the precipitation that falls on it in warm weather (Moran, et al., 2004). Van Woert, et al. (2005) found a similar result during their experiments, and stated that, "On average green roofs can retain 61% of total rainfall and during light rain events less than 2mm daily, green roof retained up to approximately 98% of rainfall, whereas the same green roof was capable of retaining only 50% of the heavy rain events when rainfall was greater than 6mm. On average, the runoff volume could be reduced by almost 65% while peak flow could be reduced by almost 98% of most of the rainfall less than 30 mm". Even when a green roof does not retain all the water from a storm, it can detain runoff for later release and reduce the runoff rate (U.S. Environmental Protection Agency, 2008). Such impacts are relevant to any city because as a result of the city's combined sewage and storm water drainage systems, the city's sewage treatment system is overburdened during moderate and heavy precipitation. Nonetheless, the city is responsible for keeping its waterways clean under the federal Clean Water Act (U.S. Environmental Protection Agency, 2011f). City spends billions of dollars for new infrastructure to reduce combined sewage overflow (Rosenthal et al., 2008). Adopting green roofs on a large scale can reduce such additional infrastructure burdens. A German study also revealed that a green roof retained more phosphate as it matured, with the retention percentage increasing from about 26 percent in the first year to 80 percent in the fourth (Köhler, 2006).

1.8.7 Air Pollution Mitigation and Health Care

Like other forms of vegetation, green roofs can filter the air by capturing particulate matter and reduce CO_2 through photosynthesis as well as reduce pollution in urban environments from ground level ozone (Banting, et al., 2005, Dousset and Gourmelon, 2003). The EPA has placed the city of Atlanta in a non-attainment region because of higher ozone levels than the national ambient air standard. Many vegetative species are able to remove harmful chemicals and particulates from the air. In the absence of vegetation these chemicals and particulates accumulate faster, resulting in diminished air quality (Clark, et al., 2008). By reducing particulate matter (PM_{10}) pollution from 70 to 20 micrograms per cubic meter, air quality-related deaths can be cut down by around 15% (World Health Organization, 2011). Similarly, exposure to ozone air pollution at levels below the current national ambient air quality standard (based on the 0.08 ppm eight-hour average ozone level) puts 1.9 million children with asthma at risk from suffering adverse health effects (Brown, 1997)

A study in Toronto found that 10.8 square feet (1 meter) of green roof can remove 0.44 pounds of airborne particles per year, thus air-borne particulates should be reduced by 0.04 pounds per square feet of green roof (Banting, et al., 2005). Another modeling study in Washington, D.C. reported that 20 million square feet of green roof can remove annually about 6.0 tons of ozone (O_3) (Niu, et al., 2010) . Clark et al. (2008) find that greening ten percent of

Chicago roofs (6540 ha) would uptake 17,400 $MgNO_2$/year, resulting in citywide benefits of $29.2 million to $111 million annually. Greening ten percent of roofs in Detroit would decrease public health costs by $3.1 billion to $11.8 billion per year and in Chicago public health benefits would be $3.8 billion to $14.2 billion per year (Clark, et al., 2008). These benefits accrue as public benefits. Green roofs can reduce surface temperatures through evapotranspiration, which in return, decrease the energy demand for cooling, thereby mitigating emissions from electricity generation, resulting in health benefits (Brunekreef and Holgate, 2002).

1.8.8 Attenuate Stresses on Utility Infrastructure

Energy saving, stormwater management, and avoided emissions capture the main economic benefits of adopting green roofs (Clark, et al., 2008). City-wide roof greening benefits public health by reducing energy consumption and absorbing suspended particles from the atmosphere (Pledge, 2005). Deutsch, et al. (2005) estimated that greening ten percent of green roof-ready buildings in Washington, D.C. (approximately 70 ha) would reduce infrastructure costs to the city's long-term control plan (LTCP) (estimated capital cost of 1.9 billion dollars) by 10 million dollars assuming the roofs would retain 450,000 cubic meters of the 97 million cubic meters of stormwater that are managed annually. Aggregating insulation, avoided emissions, fossil fuel reduction, and infrastructure benefits, the total savings from energy production and use due to greening rooftops in Washington, D.C. ranges from $0.98 to $1.32 M annually (Niu, et al., 2010).

1.9 The Private Green Roof Adoption Decision

At a private level, stormwater benefits and energy savings drive the green roof adoption decision. For example, Clark, et al. (2008) reported on the basis of study done in Ann Arbor, Michigan that with 2,000 m^2 of conventional roof, the stormwater fee would be $340 while the green roof scenario would have fees of $160 per year. This creates more than a fifty percent saving opportunity in stormwater fees over the long run. Similarly, Niu, et al. (2010) found that energy consumption decreased by 10% in buildings with green roofs.

Health benefits at an individual level from an extensive green roof adoption have not been monetized. An individual green roof has negligible impact on air quality improvement of its surroundings. Therefore, at the private decision level, health benefits do not play a pivotal role compared to storm water fee reduction and energy savings. However, if proper policy is designed to encourage private green roof adoption with tax credits or subsidies for a greater area, health benefits could be realized through lower health care costs.

In general, private decision makers who adopt green roofs only care about the net cost accrued, net benefit, and personal satisfaction. Some private green roof adopters may install green roofs for aesthetics with vegetation layers of diverse textures and seasonal color, in contrast to a rock ballast or dark surface (Weiler and Scholz-Barth, 2009). Some researchers have also noted that green roofs add value to the property price; however, the monetization of added value has not been computed so far (Acks, 2006, Banting, et al., 2005, Weiler and Scholz-Barth, 2009). For example, some developers in Tokyo, Japan have begun to install elaborate roof gardens, which significantly increase the value of the building (Pledge, 2005).

1.10 Social versus Private Optimal Decision

Sporadic private adoption of green roofs in a wide area is associated with an individual's perception of deriving the highest economic benefit realized through the lower stormwater fee, energy saving and better aesthetics. Sporadic adoption of green roofs may not produce the optimal benefit for both private and public levels. The private adoption decision of green roofs can be influenced by proximity to another green roof because of the positive externality associated with a green roof. Every installed green roof has positive spillover effects to its surroundings in the form of ambient air cooling and better aesthetics (Weiler and Scholz-Barth, 2009). Therefore, there are high chances that every roof in a city may not need a green roof to achieve the socially optimal level of greening, a point at which total welfare (social benefit) surplus is maximized. However, determining what is optimal for society is a difficult and often contentious undertaking for non-market goods (Goodstein, 2010). Spatial location of an adopted green roof may influence its neighbor's green roof adoption decision due to positive spillover effect and overall adoption rate for a city.

The above argument is demonstrated in the figure below. For example, in an urbanized neighborhood of nine building blocks (3x3), the spatial pattern of green roofs can influence the neighbor's adoption decision. As in figure 1.1, grid box 2 and 4, green roofs surrounds three conventional roofs. Therefore, it is plausible to argue that the middle three buildings may enjoy better quality air, better aesthetic views, reduced air temperature, and reduced energy demand without any cost. The benefits of these three buildings will be similar to building with green roofs. Such a situation creates an opportunity for free riders. The particular building owner may enjoy external benefits without incurring any costs. The marginal social benefit of these three buildings is greater than the marginal private benefit of the green roof adopters. Therefore, such individuals may not be interested in installing a green roof.

Spatial location of a property and its proximity to a green roof does influence next-door neighbors' private adoption decisions. Building a hypothesis on the above scenarios and consequences, it can argued that the spatial location of green roofs influence the private adoption decision as well as the social optimal adoption rate of green roofs on a citywide scale. Therefore, a systematic spatial analysis of green roof adoption needs to be examined incorporating benefit a cost analysis for a city like Atlanta to achieve social optimum as well as private optimum levels of green roofs to mitigate the consequences of urbanization. Different green roof adoption scenarios and the impact on nearby buildings can be tested using Geographic Information System (GIS).

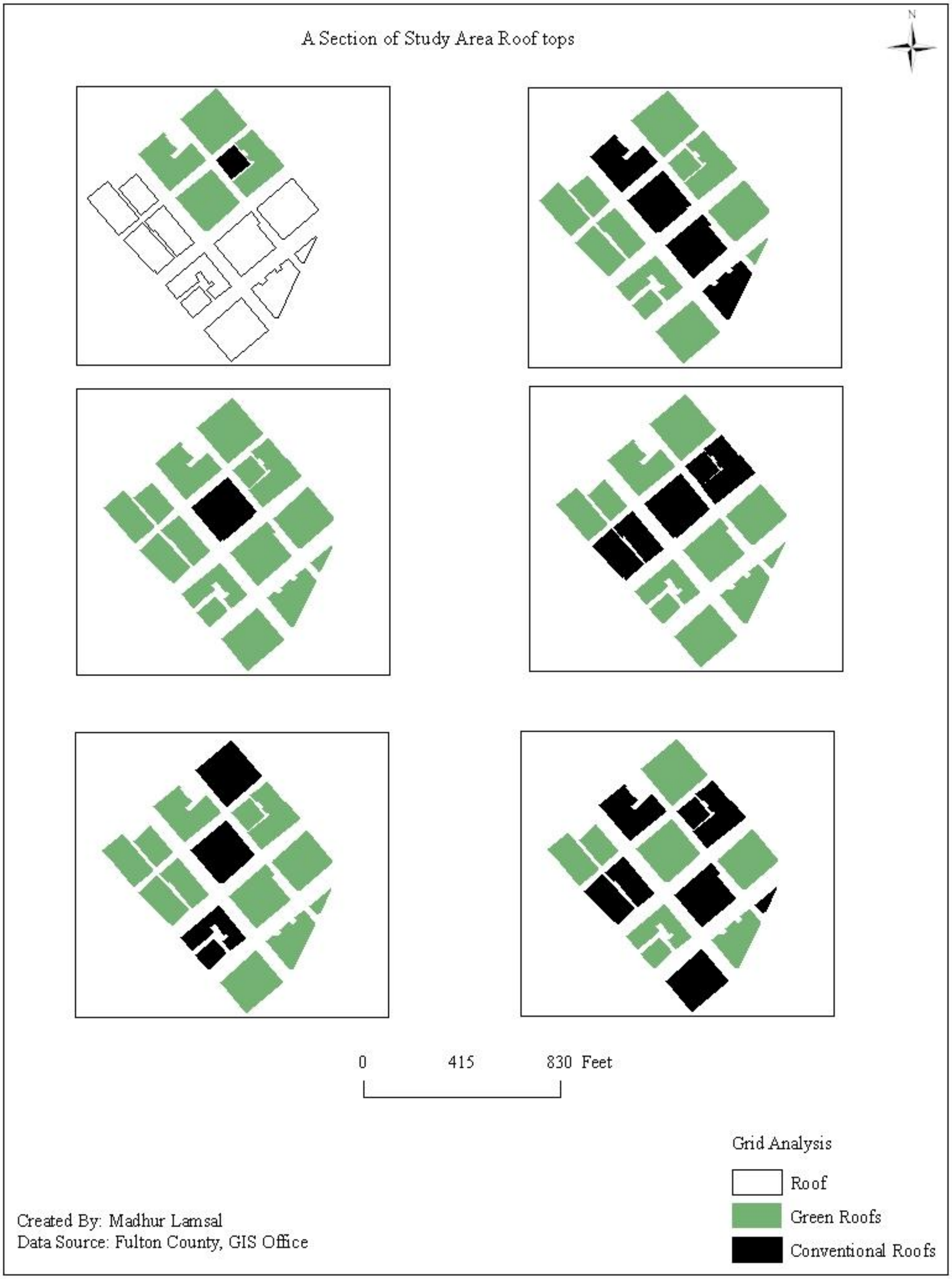

Figure 1.1: Section of Study Area Grid Analysis

1.11 Objectives

The objectives of this research are to

- Estimate, from a private perspective, the costs and benefits associated with installing and maintaining an extensive green roof in the city of Atlanta.
- Estimate, from a social perspective, the costs and benefits associated with installing and maintaining an extensive green roof in the city of Atlanta.
- Conduct sensitivity analysis on key parameters associated with private and social adoption decisions.
- Identify specific buildings for which public incentives for green roof adoption should be considered, i.e., buildings for which it is socially but not privately optimal to install a green roof.
- Examine the impact of positive externality on private and social adaption decisions.

1.11 Overview of Thesis

This thesis is composed of five chapters: Introduction, Economic Foundation, Data and Methodology, Results, and Conclusions and Recommendations. Chapter 2 summarizes economic theory related with environmental economics and non-market goods and ties the current limitations of the green roof market structure as discussed by previous researchers. Data and methodology is discussed in chapter 3. Chapter 4 presents all results and adoption pattern analysis in detail. Chapter 5 covers the conclusion and recommendations for research.

CHAPTER 2

ECONOMIC FOUNDATION AND REVIEW

2.1 Preface

The primary purpose of this chapter is to define the economic background and outline the theoretical foundation that is related to green roof adoption, the green roof market, and its components. Energy savings, reduced stormwater fees, and better aesthetic view drive the green roof adoption, at an individual level. A handful of private companies, research centers, and government agencies have been promoting green roofs as a mitigation tool to improve air quality, reduce the urban heat island effect, and lower stormwater infrastructure costs in the U.S. (Banting, et al., 2005, Niu, et al., 2010, Rosenzweig, et al., 2006). Promoting an environmental program or policy like green roof technology requires detailed analysis of associated fundamental economic principles. The following section defines and explores related economic terms, theories, and principals that influence promoting environmental programs like green roof technology.

2.2.1 Definition of Economic Terms and Theory

2.2.1 Damage Function

Damage can be defined as the product of an act that reduces health, value, or usefulness of something causing unwanted external costs to any agent. Damage means all the negative impacts that users of the environment experience as a result of the degradation of the environment (Field, 1994). There are many types of negative impacts that vary from one environmental asset to another. For example, each year in the United States, 20,000 lives are lost because of suspended particulate matter of size 2.5 microns or less in diameter. A damage function shows the relationship between the source of damage and the damage those sources cause (Field, 1994). In the case of urbanization, a damage function tells us how the environmental damage varies with the urbanization rate, and what the monetary value of that damage is.

2.2.2 Abatement Cost

Abatement cost is the cost incurred by firms or agents for the removal or reduction of negative byproducts that they themselves have created. For example, modern sewer systems avoid combined sewage overflow but stormwater runoff still carries toxic contaminants from streets and sidewalks that get discharged at nearby receiving water bodies imposing costs of cleaning (Pledge, 2005). New York City has allocated $1.8 billion for combined sewage overflow abatement projects (Pledge, 2005), suggesting that there is a huge abatement cost involved if the mandated ceiling is violated.

2.2.3 Private Cost

Private cost includes the internal cost incurred for inputs, labor, rent, and depreciation. The private costs of an action as in the case of conventional and green roofs are installation, maintenance, energy, and stormwater fees.

2.2.4 Private Benefit

Private benefit is the benefit to an individual or an economic agent, such as a consumer or firm, from an event, action, or policy change. The private benefits associated with green roofs are discussed in chapter 1.

2.2.5 Social Cost

Social cost is the cost to society as a whole from an event, action, or policy change. Social costs include private costs, but also may include much more in certain situations (Field, 1994).The social costs borne due to urbanization are additional investments needed for utility upgrades. The social costs of green roof technology can be the costs of the action such as monitoring and administration of green roof programs, no matter who experiences it.

2.2.6 Social Benefit

Social benefit is the benefit to society as a whole from an event, action, or policy change. For example, if green roof technology is implemented as one of the tool to mitigate the effects of urbanization, some of the social benefits (as listed by Green Roof for Healthy Cities (GRHC), a nonprofit organization) are: stormwater management, improved air quality, moderation of the urban heat island effect, aesthetic improvement, and local job creation (Green Roof for Healthy Cities, 2012).

2.3 Theoretical Foundation

2.3.1 Externality

An externality is a cost or benefit of an economic activity borne as a byproduct and such cost or benefit is not governed by a price mechanism. For example, in a rapidly growing city, additional costs are borne to mitigate the urban heat island effect for infrastructure improvement, for stormwater management, to supply higher energy demands, and to reduce health care costs. These external costs are passed on to society.

In the case of green roof technology, externality is positive externality, as for example, green roofs absorb anthropogenic suspended particles from the atmosphere and clean the air. They also provide better aesthetic views as well as reduce stormwater and energy bills. Green roofs can mitigate the effect of the above mentioned negative externalities to some extent if adopted in large scale for any city by the means of appropriate policy (Banting, et al., 2005, Booth, 1991, Clark, et al., 2008, Liptan, 2003, Niu, et al., 2010, Rosenzweig, et al., 2006, Weiler and Scholz-Barth, 2009). If proper policy is not devised, positive externality does not produce socially optimum output because the benefit to the individual or firm is less than the benefit to society. In the case of positive externality, less is produced and consumed than the socially optimal level.

A green roof in a neighborhood can be viewed as a public amenity because it helps to clean air as well as provide a better aesthetic view. Everybody in the vicinity will enjoy the better aesthetic view. There are economic theories that suggest such cost-free benefits ultimately lead to market failure in the case of public goods (Field, 1994, Goodstein, 2010). Many researchers agree upon the fact that every green roof has positive effects in a society regardless of its size (Weiler and Scholz-Barth, 2009). As the rate of green roof adoption increases, the net private benefits decrease, thus when a positive externality exists in an unregulated market, the marginal benefit curve, the demand curve, of the individual making the decision of adoption is less than the marginal benefit curve to society (Field, 1994). This gives an opportunity for a free ride. When a public benefit is being produced due to an action such as green roof ambient air cooling and better aesthetics, each person may have an incentive to free ride on the efforts of others (Field, 1994). The following two graphs suggest how both positive and negative externality can lead to market inefficiency.

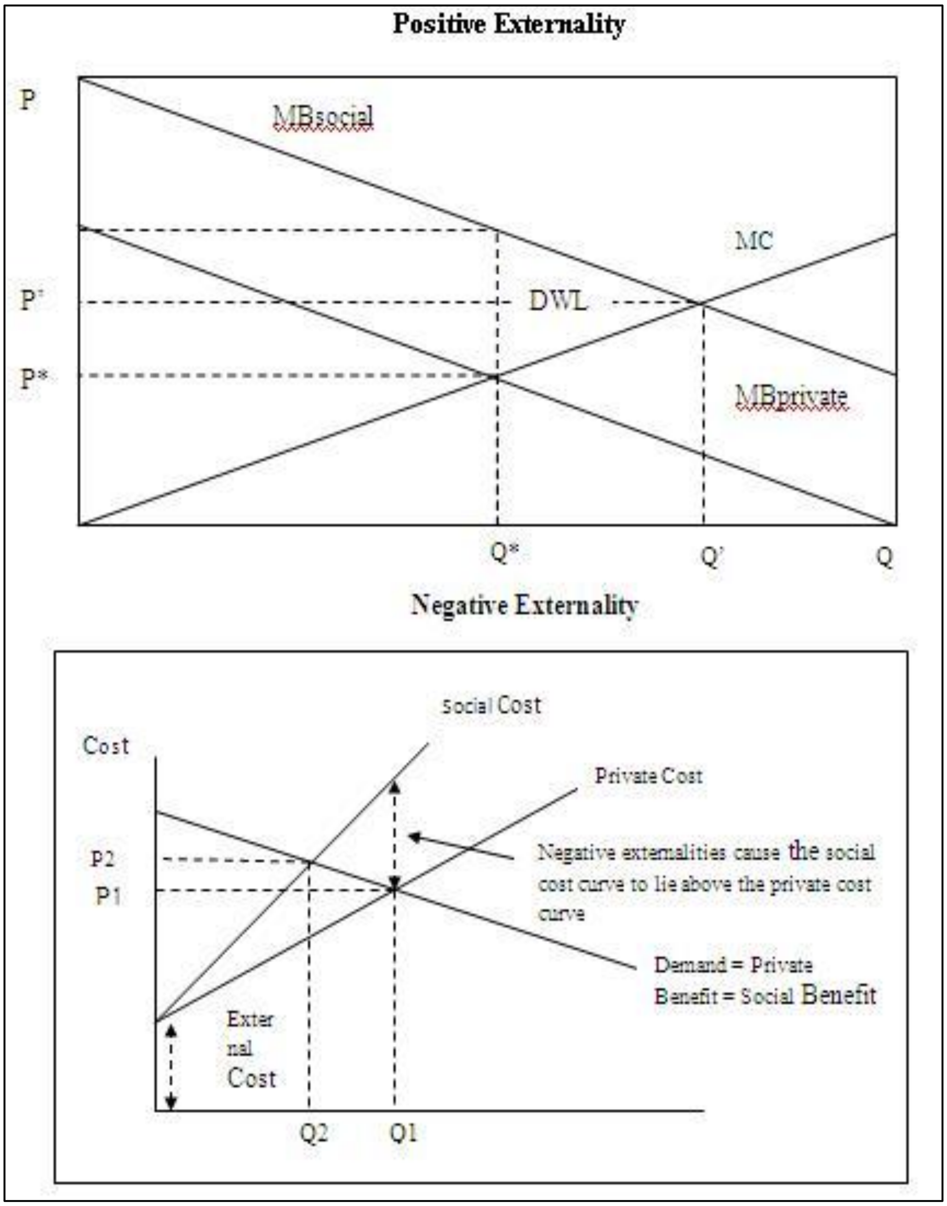

Figure 2.1: Positive and Negative Externality

2.3.2 Pareto Efficiency

Pareto efficiency is a fundamental measure employed in public policy decision making before a policy gets enacted. The Pareto criterion is defined as, "A policy change is socially desirable if, by the change, everyone can be made better off, or at least some are made better off, while no one is made worse off" (Just, et al., 2005). Pareto improvement is achieved by making someone better off without making anyone worse off. Policy makers often use this criteria because, as stated by Goodstein (2010), "Conditional on the existing distribution of income, it makes the 'economic pie' as big as possible. In fact, at the efficient outcome, the net monetary benefits produced by the economy will be maximized" (Goodstein, 2010).

As in green roof technology, the adoption decision incurs higher private costs but benefits not only the adopter but society as well. For example, only a few members of society benefit from proximity to different amenities like malls, hospitals, airports and highways. However, byproducts like poor air quality because of reduced vegetation impose costs on all of society in many forms. The Pareto efficiency standard seeks a level of green roof adoption rate where net benefits are the greatest. It is often very difficult to calculate the optimal level for any policy that is also efficient. Therefore, policy makers rarely seek to exactly achieve the economically efficient level; instead they focus on a rough benefit-cost test, rules of thumb, qualitative environmental standards, and or general guidelines such as safety standards for human or ecological health (Nguyen, et al., 2006). When the efficiency standard is impractical to implement, policy makers often turn to other standards (Keiser, 2009). One of these standards, the environmental standard, is discussed below.

2.3.4 Environmental Standards

The USEPA, under the Clean Air and Clean Water Acts, reviews, updates and sets regional environmental standards every five years. Since it is difficult to calculate the Pareto efficient level for non-market goods like air and water quality, policy makers often chose environmental standards to define a cap level for pollutants. The greatest impact of urbanization is felt upon ambient air and water quality of a city. The safety standard, or human standard, is an environmental policy standard that is based on the idea that no excessive harm should be done to humans (Keiser, 2009). Regulatory agencies frequently define safe pollutant levels where there is a cancer risk of less than one in 1 million (Goodstein 1995). The environmental standards of every city need to fall well under national standards such as NAAQS and NPDES.

2.3.5 Cost Benefit Analysis

Cost-benefit analysis has become the primary analytical method of evaluating public programs (Field, 1994). Field (1994) adds that a cost-benefit analysis is performed to determine how well, or how poorly, a planned action or policy will turn out. A cost-benefit analysis finds, quantifies, and adds all positive factors and benefits, then identifies, quantifies, and subtracts all negative costs. The difference between the two indicates whether or not the planned action is advisable.

The USEPA, as well as other federal agencies, have sought to develop better methods for estimating the benefits and costs of environmental programs such as green roof technology. The cost-benefit analysis is not the only or always the best approach. Two of these alternative methods are summarized below.

2.3.6 Cost-Effectiveness

An environmental policy is cost effective if it produces the maximum environmental improvement possible for the resources being expended or, equivalently, it achieves a given amount of environmental improvement at the least possible cost (Field, 1994). The cost-effectiveness analysis seeks to identify the least costly way in which to achieve a given objective, without asking whether there is any economic justification for achieving that objective (Bergstrom and Randall, 2010). The economic notion of cost-effectiveness is a criterion by which economists judge policy instruments. Cost-effectiveness analysis is advisable where benefits are not explicitly quantifiable in economic terms other than cost (Field, 1994). Many academic researchers have quantified the associated costs and benefits with green roof technology. Therefore, this research does not rely on cost effectiveness approach.

2.3.7 Risk-Benefit Analysis

Risk benefit analysis compares expected project benefits with the expected economic value of potential environmental, property, and human hazard (Bergstrom and Randall, 2010). In green roofs, potential ecological (environmental) and human hazard are only possible when a green roof adopter overlook suggested architectural criteria or plant vegetation that are not suitable for their region (Oberndorfer, et al., 2007). Researchers have been able to identify risk associated with green roof technology (Oberndorfer, et al., 2007, Pledge, 2005, Weiler and Scholz-Barth, 2009). Therefore, risk-benefit analysis does not apply as a primary economics tool in this study.

2.3.8 Coase Theorem

The Coase Theorem, named after the economist Ronald H. Coase, states that regardless of the distribution of initial property rights, if polluters and those affected by this pollution are able to negotiate freely, they arrive at the efficient level of pollution. It describes the economic efficiency of an economic allocation in the presence of externalities.

In the case of a wide area of green roof adoption, positive externalities mean that social cost is less than private cost, and more of the good should be produced than will occur in a free market (Just, et al., 2005). If parties (household, government, and market) can bargain without cost involved over the rate and patterns of adoptions, then the private market can always solve the problem of externalities. It can also achieve optimal incentive or subsidy structure efficiently, irrespective of how the law assigns responsibility for damages due to urbanization.

A corollary to the Coase Theorem addresses its application to trading and cost-effectiveness. If there is a well-functioning credit market, a cost-effective outcome will be achieved by a marketable credit system regardless of the initial ownership of the credits (Goodstein 1995). The Coase Theorem, its relevant corollary, and the ability to achieve cost-effectiveness can form the theoretical foundation of trading (Goodstein, 2010). But currently, there is no emission allowance trading market for green roof benefits (Clark, et al., 2008). However, trading has comparative advantages over alternative methods. Two of these alternative methods are discussed below.

2.3.8 Command and Control

In the case of environmental policy, the command and control approach consists of relying on standards of various types to bring about improvements in environmental quality, where standards are mandated level of performance that is enforced by law (Field, 1994). For example, many cities in U.S. charge storm water fees that are based on the total impervious surface over total property area (Hathaway, et al., 2008). Due to the presence of heterogeneous abatement cost curves of effects of urbanization among city dwellers, a cost-effective solution will often be impossible to achieve under command and control regulations.

2.3.9 Pigovian Taxes

A Pigovian tax is a fee levied on a market activity that generates negative externalities (Field, 1994). By law, regulatory agencies cannot tax individual residents for degrading air quality or creating an urban heat island. However, taxes that are equal to abatement costs have been used and offer a few advantages: they are fairly easy to administer and they provide a source of revenue to the regulatory agency. But a major difficulty with Pigovian taxes is determining the appropriate tax level (Kahn, 2005). Carbon tax can be categorized as a Pigovian tax.

2.3.10 Pigovian Subsidy

A Pigovian subsidy is an incentive given on market activity that generates positive externality. If there were positive externalities instead of negative externalities, one would want to encourage these behaviors by subsidizing them instead of taxing them. Many researchers have found that regardless of the location and extent of a green roof or natural landscape over structures, the benefits of a single green roof installation is great (Acks, 2006, Liptan, 2003, Weiler and Scholz-Barth, 2009).

In the presence of positive externalities, the social cost of a market activity is covered by the private cost of the activity (Field, 1994). Therefore, Pigovian subsidies may increase market activity of green roof technology. Subsidies or tax credits given to a green roof adopter will help the market reach economic efficiency. Pigovian subsidies internalize the externality into the agents' utility function by giving the government incentive to subsidize more than it otherwise would (Field, 1994). A subsidy encourages a consumer to consume more of the good that has positive externality. In the case of green roof technology, a subsidy will increase the marginal benefit people receive when they consume the good.

2.4 Essential Component

2.4.1 Challenges of Green Roof Market

The main challenge for green roof adoption is the higher initial cost of installation. Other obstacles to green roof projects may vary in scope and impact. There are concerns over green roof options, methods, materials, designs, and expertise available in the market (Weiler and Scholz-Barth, 2009). For example, before installing a green roof, one should consider whether the building is strong enough to support the additional weight. Green roofs can add 30–120 lbs per square foot (Weiler and Scholz-Barth, 2009). Therefore, before installing a green roof, investments in upgrading the structure of the building may be required for older buildings. This adds to the initial cost. Green roofs can require special care, particularly if the growth media and plants are not selected properly (Pledge, 2005, Weiler and Scholz-Barth, 2009). There are not enough demonstration projects to inspire and give confidence to the general public to adopt green roofs in large scale, especially in North America and Australia (Williams, et al., 2010).

2.4.2 U.S. Green Roof Market Frameworks

The forecast value for the North American roofing market is $18 billion in 2014 with the most rapid gains expected in alternative roofing technologies, including green roofs (Newswire, 2010). The actual size of the green roof market in North America was predicted to be around 7 million square foot in 2010 (Narejo, 2010). Municipalities, school boards, auto companies, and hospitals have undertaken many large green roof projects. The starting cost of a green roof can be close to $30 per square foot (Pledge, 2005). The roof may pay off with savings in energy efficiency and the life of the roof in the long term, but initial investment can be significant. This can be enough to kill a project if funds are hard to come by (Narejo, 2010). The residential building construction market, which accounted for 58 percent of total roofing demand in area in 2009, is still skeptical to use green roofs as a better alternative. Asphalt shingles remained the most popular roofing product, and demand for asphalt shingles is expected to accelerate at an above average pace through 2014, fueled by rebounding housing starts (Newswire, 2010).

The factors that influence the growth of the green roof market can be placed into four categories: regulatory, environmental, aesthetic, and economic. The specific contribution of each factor is hard to quantify. The regulatory support typically takes the shape of ordinances, bylaws, zoning decisions, and tax incentives (Liptan, 2003). For example, in Portland, Oregon, all new city-owned buildings are required to have green roof that covers 70% of the roof area. The number one environmental factor helping with the green roof market growth is the increased concern over the combined sewer overflow problem found in nearly every North American city (Narejo, 2010).

2.4.3 Clean Air and Water Act

The EPA has mandated certain levels for air and water quality in every U.S. city under the Clean Air Act and Clean Water Act. It is the EPA's job to set NAAQS and maximum allowable concentrations-for six criteria pollutants: ozone (O_3), particulate matter (PM), nitrogen dioxide (NO_X), carbon monoxide (CO), sulphur dioxide (SO_2) and lead (Pb) (Brown, 1997). Similarly, the EPA also monitors and sets standards for water quality that have to be maintained in navigable water bodies under the Clean Water Act. State governments must devise cleanup plans to meet the EPA's standards. Despite federal rules and regulations for clean ambient air quality, many cities such as Atlanta, GA still fall under non-attainment regions.

2.4.4 Agency Participation

Narejo (2010) found that in "North America, the green roof market remains immature despite the efforts of several industry leaders and government. In Europe however, these technologies have become very well established especially in Germany. This has been the direct result of government legislative and financial support, at both the state and municipal level. This support has led to the creation of a vibrant, multi-million dollar market for green roof products and services in Germany, France, Austria and Switzerland. In Germany for instance, the industry continues to experience growth with 13.5 million square meters of green roofs constructed in 2001, up from 9 million square meters built in 1994." Green Roof for Healthy Cities (GRHC) quotes that, "Such support recognizes the many tangible and intangible public benefits of green roofs. Environmental factors are often the drivers of regulatory support. Cities with the most active green roof market are the ones that have clear regulatory support for green roofs."

Stakeholder participation plays a key role in determining the supply and demand of incentives and subsidies. For various reasons, stakeholders may decide to participate or withdraw support for green roof technology. These reasons may include fundamental beliefs for and against green roofs, the cost of participation, or level of difficulty in getting satisfying credit certification from Leadership in Energy & Environmental Design (LEED), is a green building rating system developed by the U.S. Green Building Council (U.S. Building Council, 2012). The EPA handbook provides a few methods for engaging stakeholders in the case of non-market public goods such as air and water quality improvement.

2.4.5 Efficient Market Structure

It is very difficult to choose one market structure that best fits green roof technology market because the inputs of green roof market (material, labor charges, and maintenance cost) are easy to monetize but the benefits of green roofs are harder to monetize. However, some studies (Acks, 2006, Banting, et al., 2005, Clark, et al., 2008, Liptan, 2003, Weiler and Scholz-Barth, 2009) suggest that picking the most efficient market structure may be possible. If municipalities provide incentives such as allowing developers to increase the floor area ratio, or lowering or even forgiving taxes, living green roofs become cost effective immediately (Weiler and Scholz-Barth, 2009).

Tax incentives in Chicago have sustained green roof growth for nearly 10 years (Narejo, 2010). In recent years, municipalities have been moving toward stormwater fees based upon total impervious surfaces on a property, creating an opportunity to “credit” green roofs for a stormwater reduction (Clark, et al., 2008). Policies that make stormwater infrastructure expenses more transparent to the citizenry through storm water fees or market-based tradable permit schemes for contributions to impaired local waterways are two strategies that have the potential to rectify the price discrepancy (Clark, et al., 2008). The EPA uses the Clean Air Market

Programs, called "allowance trading" or "cap and trade" emissions trading approaches that allow sources to buy and sell allowances on the open market (U.S. Environmental Protection Agency, 2011e).

As Hoag and Hughes-Popp (1997) note, “A fixed price, based on average cost, eliminated the marginal cost benefits that are crucial for efficient trading.” Clark et.al (2008) suggest, “Translating the air pollution mitigation ability of green roofs into an economic benefit to the technology would further reduce the net present value of green roofs; this could be achieved through direct incentives reducing the upfront cost of green roofs or through incorporation of green roofs into existing regional air pollution emission allowance markets. To quantify the benefits of reducing Nitrogen dioxide (NO_2) emissions for building owners, green roofs could be integrated into the existing air emission allowance markets. If green roofs are considered an abatement technology, the incorporating sinks into cap-and-trade programs could allow the pollution taken up by the green roof to be traded on the open emissions allowance market. Such a program does not currently exist, in part due to the constraints place on the demonstrations that a new technology fits abatement criteria.”

Trading of public goods is also found in the following market structures:

i). Bilateral Negotiation – direct negotiation between buyers and sellers of credits.

ii). Clearinghouse – a third party acts as a broker for those willing to buy and sell credits.

2.4.6 Enforcement and Transaction Costs

Enforcement and Transaction costs are defined as the additional costs borne due to a change in policy or economic transaction. In the case of green roof technology, traction costs include the costs to establish an air quality allowance market, monitor air and water quality, issue credits, and resolve disputes among parties. Few studies have used proxy estimation for transaction costs and suggested that such costs are less than the overall benefits of green roofs (Acks, 2006, Banting, et al., 2005, Clark, et al., 2008, Currie and Bass, 2008, Liptan, 2003, Yok Tan and Sia, 2005). This research does not consider such cost for this study and hence are not included in cost-benefit, net present value, and scenario analyses.

CHAPTER 3

DATA AND METHODOLOGY

3.1 Basics of Green Roofs

Flat roof surfaces represent a significant percentage of impervious surfaces in any city. Such area can be replaced with vegetation. A German landscape architect, Professor Hans Luz, conceptualized roof areas as an opportunity and proposed the use of green roofs as a means of improving the quality of urban environments (McDonough et.al, 2003). Germany is regarded as the place of origin of modern-day green roofs and their adoption has spread to its neighbors as many European countries offer incentives to green roof adopters. Currently, Europe is the leader of green roof technology whereas green roofs are a fairly new concept for North America.

3.2 Types of Green Roofs

There are two types of green roofs: extensive and intensive.

3.2.1 Extensive Green Roofs

Extensive green roofs have a very shallow depth of soil or growing medium and are primarily used for environmental benefits such as stormwater management and insulating properties. The media depth ranges from 8-15 cm, therefore plant species are limited to herbs, grasses, mosses, and drought-tolerant succulents such as sedum. They are seldom irrigated and require minimum maintenance (Weiler and Scholz-Barth, 2009). Extensive green roofs are non-accessible and non-recreational. They can add up to 13-15 lbs/sf and can be built on sloped surface also. However, the ideal roof slope for an extensive green roof is between 5 - 20 degrees because water drains naturally due to gravity (Weiler and Scholz-Barth, 2009). This study is limited to the application of extensive green roofs.

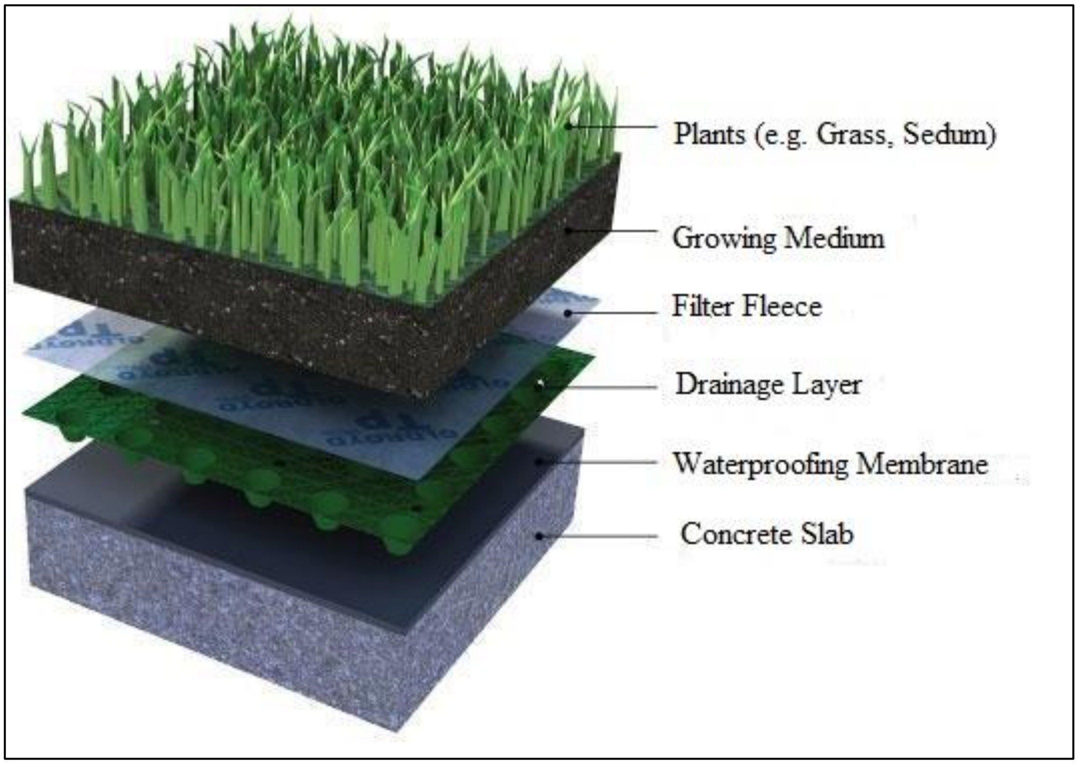

Figure 3.1 Cross Section of Common Green Roof System (Ref: www.roof-garden-guides.blogspot.com)

3.2.2 Intensive Green Roofs

Intensive green roofs have a greater depth of soil or growing medium, which allows for greater diversity in size and type of vegetation. They require regular irrigation as well as maintenance. Roof gardens are one kind of intensive green roof (Weiler and Scholz-Barth, 2009). They can hold a wide variety of plant species that may include trees and shrubs and therefore require deeper media depth, usually >15.2 cm.

Figure 3.2 Intensive Green Roof over the Chicago City Hall (Ref: www. en.wikipedia.org)

3.3 Cost of Green Roofs

Green roof installation cost varies more than conventional roofs according to design and function (Weiler and Scholz-Barth, 2009). Extensive green roofs are considered the cheapest, lowest maintenance, lowest weight per area unit and generally use plants from the sedum family. Intensive green roofs are more expensive, require regular maintenance and can be suitable for native flora. Most academic researchers rely on available data of extensive green roofs (Clark et.al, 2008). The USEPA has listed installation cost ranges of \$5-\$25/ft^2 and \$25-\$40+/ ft^2 for extensive and intensive green roofs respectively.

3.4 Study Area

The study area lies in the business district of downtown Atlanta, a section of zip code 30303. Digitized impervious roof surface GIS data were received from Mr. Steve William, Assistant Director, GIS, Department of Information, Fulton County Government, Georgia. The City of Atlanta GIS office recently revealed a 3D model of the business district of downtown Atlanta. It was constructed combining LIDAR (Light Detection and Ranging) data and current GIS shape files. After careful review of the 3D model and comparing it with Google Earth as well as on-site inspection, a study area with relatively homogeneous building heights (fewer buildings higher than 11 floors), was selected. Buildings with greater than 11 floors were not included for study because as the number of floors increase, the ratio of roof surface to floor area decreases. Therefore, the percentages change in energy cost, a potentially significant benefit of green roof-decreases as the number of floors increases. Also green roof at such a height do not affect ground level microclimates (Alexandri and Jones, 2008).

A circular area of 1235035.99 m^2 (0.477 $mile^2$) was extracted from digitized shape files using Arc GIS. The number of floors of each building were counted using Google Earth v. Pro and on-site inspection was used to confirm the number of floors. There were 184 flat impervious polygons located within the study area. Of those, 22 polygons were found to be consolidated polygons. Therefore, Google Earth v. Pro was used to compute the separate roof area of individual buildings out of the consolidated polygons. Using GIS editor tool, 218 polygons were identified.

Roof sizes less than 208 m^2 were not included in the study because greater roof sizes can produce higher public benefit and can be viable candidate for subsidies. Of the 218 polygons, there were 26 buildings with more than 11 floors, 33 rooftops smaller than 208, three roofs were attics, and 18 were parking lots, all of which were excluded from the study. The remaining 138 flat rooftops were chosen as viable candidates for the study. The average number of floors of the selected buildings is four. The impervious area of 138 rooftops is 250782.16 m^2, which is 19.02% of the total study area. And average roof size is 1702.41 m^2.

Table 3.1 Study Area Details

Descriptions	Polygons	Area (m^2)	Average (m^2)
Study Area (Radius = 626.87 m)		1,235,036	
Total Roofs in Study Area	218	410,926	1,884.98
Dropped (buildings > 11 Floors, Small Roof Area < 208 m^2, and Parking Lots)	80	160,144	2,001.80
Selected Roofs for Green Roof Study	138	234,933	1,702.41

The following two maps of the study area were created incorporating Arc GIS v.10 and Google Earth v. Pro.

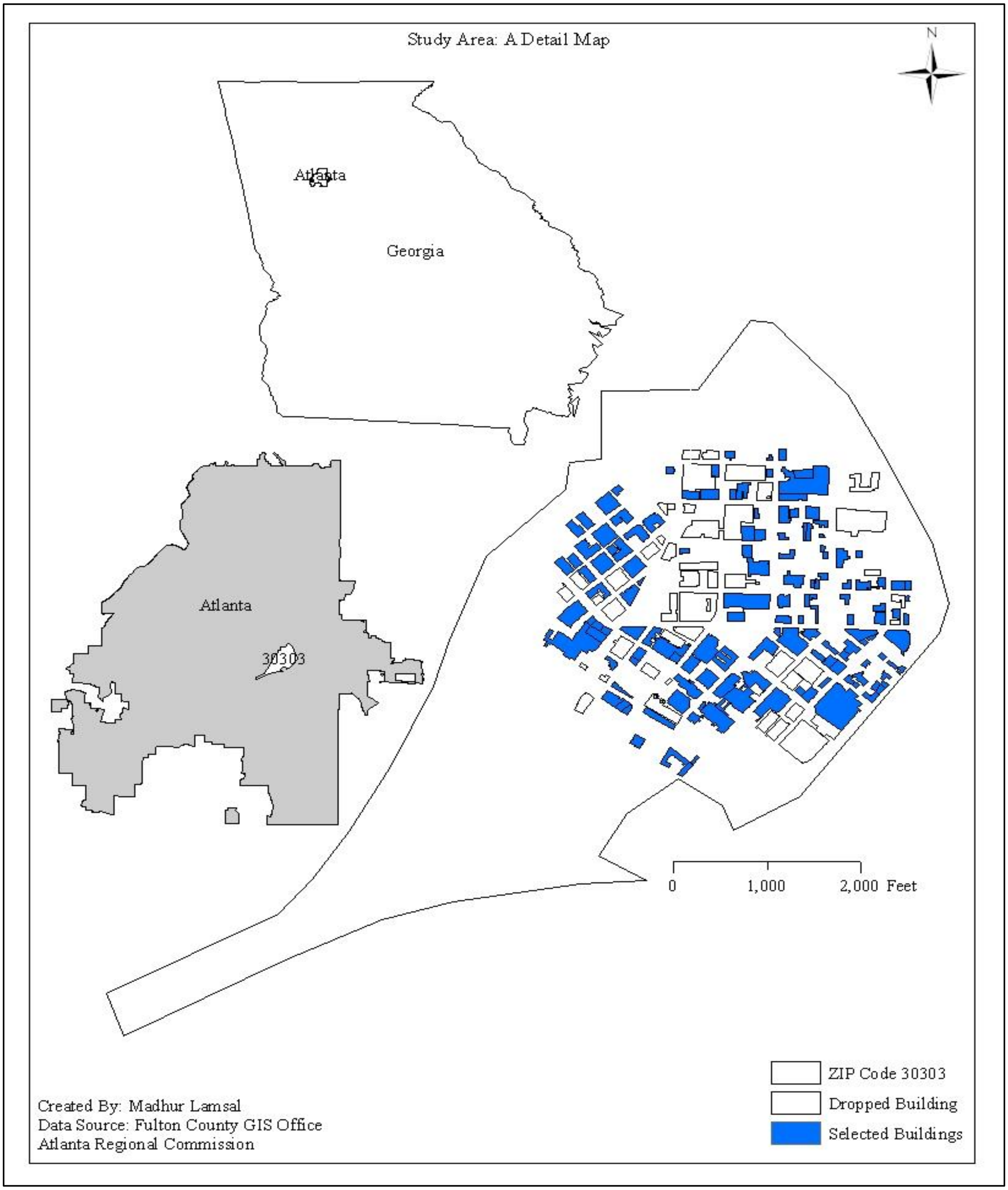

Figure 3.3: Study Area GIS Map

Figure 3.4: Proposed Green Roofs Overlapped on Google Earth Image.

3.5 Theories and Calculation

The net present value (NPV) of both a conventional and green roof, for one 40-year roof cycle was calculated using equation 3.2 for three rate and methods used in three different recent studies to confine the range of cost-benefit for the study. Equation 3.1 represents the private and public costs associated with conventional and green roofs.

$$Total\_Cost(C) = f(I, M, E, S)_{private} + g(HC, SI, PEC)_{public} \qquad 3.1$$

Where *I*= Installation Cost, *M*= Maintenance Cost, *E*= Energy Cost, *S*= Stormwater Cost, *HC*= Healthcare Cost, *SI*= Stormwater Infrastructure Cost, and *PEC*= Plant Emission Cost

$$NPV_{CR,GR} = \sum_{t=0}^{40} \frac{C(I, M, E, S, HC, SI, PEC)}{(1+r)^t} \qquad 3.2$$

Where *CR*= Conventional Roof, *GR*= Green Roof, *t*= year, and *r* = discount rate

The net benefit was calculated by subtracting NPV_{CR} from NPV_{GR}. The method of parameterizing and calculating specific private and public costs and benefits associated with conventional and green roofs are discussed below.

3.6 Installations and Maintenance Cost of Conventional and Green Roofs

Different studies have used different dollar amounts for installation and maintenance costs of conventional and green roofs. The costs of installation and maintenance vary according to location.

This study utilizes three installation rates from recent literature. Carter, et al. (2008) carried out their study for Athens, Georgia, Clark, et al. (2008) and Nui, et al. (2010) were based in Ann Arbor, Michigan and Washington, D.C., respectively.

Acks (2006) estimated the maintenance costs as $0.10/ft^2 and $0.60/ft^2 for conventional and green roofs respectively. The maintenance costs for a conventional roof occur annually and green roof maintenance costs occur every two-year after the installation. Maintenance costs in this study are based on Acks (2006). The installation cost for each building was calculated by multiplying the area and rates for both conventional and green roofs using three rates of following three studies.

Table 3.2: Conventional and Green Roof Installation Rates

Study (Methods)	Conventional Roof Rate/m^2	Green Roof Rate/m^2
1. Carter, et al., 2008	$83.78	$155.41
2. Clark, et al., 2008	$167.00	$232.00
3. Nui, et al., 2010	$242.00	$309.00

3.7 Conventional Roof: Cost Calculation

3.7.1 Energy Cost

Estimates of the energy consumption, in KWh, and charged electric utility rate per m^2 for each building were generated by Energy Plus v.6.0, a building energy simulator developed by the U.S. Department of Energy (DOE). It is designed to model heating, cooling, lighting, ventilating, and other energy flows, as well as water, in buildings based on climate, building use, material and size inputs (U.S. Department of Energy 2011a). The input criteria allow the option to choose internal state and city climate data, while other required information such as roof surface area, number of floors, roof type, wall type, and building type[2] for each building was manually entered. Building activity options were set to smart values that count 5 people/100m^2, smart electric plug intensity 8.07 W/m^2 , and gas appliance intensity 0.3 W/m^2. Annual energy cost was calculated multiplying rate, roof area and number of floors.

3.7.2 Stormwater Cost

Currently, the city of Atlanta does not charge an itemized stormwater fee to its citizenry. However, a stormwater fee ordinance was proposed in 2010 on the recommendation of the Department of Watershed Management of Atlanta to collect 0.27/100 ft^2 per month, which was rejected by the city council. Proposed fee is used as a proxy to calculate stormwater costs associated with a specific building's impervious surface.

3.8 Public Cost with Conventional Roof

3.8.1 Public Cost: Stormwater Management

Cities are required to clean stormwater before discharging it into nearby navigable water bodies according to the Federal Clean Water Act. Bluestone (2010) calculated that the city of Atlanta would require $3.2-$5.5 billion to spend on stormwater collection, operation, and maintenance costs from 2010-2030. Using this expenditure schedule, yearly cost is computed, which then divided by the total roof surface area of city of Atlanta to estimate the cost imposed by per m^2 roof surface area.

[2] The building type available in Energy Plus is twenty. This study has utilized office/professional and education types only. There are 25 buildings that belongs the Georgia State University.

3.8.2 Public Cost: Health Care

Energy Plus v.6.0 also provides emission of pollutants (NO_X, SO_2, CO_2, etc) from each building per year due to electrical appliances used and human activity. These pollutants produce health care costs through air pollution. The monetization of NO_x and SO_2 damage through air pollution is calculated using Muller, et al. (2007). This study found that 21 million tons of NO_X causes $6 billion dollars worth of damage and 14.8 million tons of SO_2 causes $19.5 billion worth of damages per year in the U.S. The marginal damage of $5/tC for CO_2 is derived from Tol (2004). The emission data retrieved from Energy Plus v.6 were multiplied to Muller, et al. (2007) and Tol (2004) rates to calculate public health costs imposed by each building due to the emission of NO_X, SO_2, and CO_2.

$$Health\_Care\_Cost(HC) = h(NO_X, SO_2, CO_2) \quad 3.3$$

3.8.3 Public Cost Due to Urban Heat Island Effect

The urban heat island effect is a well-observed phenomenon in the City of Atlanta (Zhou, et.al, 2010). Akbari, et al. (1992) notes that 1^0F rise in temperature due to the UHIE increased peak cooling demand by 0.5-3%. It can be hypothesized that 0.5-3% of total energy is being used to offset each 1^0F the UHIE in our study area. However, the additional cost for the UHIE was not calculated by Energy Plus v.6.0 because that model uses actual weather data that are stored; it was not possible to introduce new weather data reflecting a 1 ^{0}F, or more, reduction in temperature and rerun the model for Atlanta. As a result, Akbar et al.’s estimates of the percentage reduction in energy use were used here.

3.8.4 Health Care Damage Due to Power Production: Tracking Back to Power Plants

The USEPA has developed the Emissions & Generation Resource Integrated Database (eGRID), a comprehensive inventory of environmental attributes of electric power systems (U.S. Environmental Protection Agency 2011d). The preeminent source of emissions data for the electric power sector, eGRID is based on available plant-specific data for all U.S. electricity-generating plants that provide power to the electric grid and report data to the U.S. government. Data reported include generation in megawatt-hour (mWh), resource mix (for renewable and nonrenewable generation), and emissions in tons for nitrogen oxides (NO_x,), sulfur dioxide (SO_2), carbon dioxide (CO_2), and other emissions. The eGRID reports this information on an annual basis at different levels of aggregation (boiler, generator, plant, companies, and grid regions of the country) (U.S. Environmental Protection Agency, 2011d).

The total annual energy consumption by the study area is computed by summing all building annual consumption data. The USEPA Power Profiler tool is used to determine the power grid region based on the zip code 30303 and it also provides the information on the fuel mix used to produce the energy for the zip code and emission rate of pollutant per megawatt hour (U.S. Environmental Protection Agency 2011b). The Energy Star Profile Manager, another tool developed by USEPA was used to find the exact utility provider for our study area: zip code 30303 (U.S. Environmental Protection Agency 2011a). Georgia Power (GP) is the sole electricity provider for the zip code 30303.

The USEPA Power Profiler suggests that 52.2% of electricity used in zip code 30303 comes from coal-fired power plants. However, according to a Georgia Power fact sheet, the percentage of coal-generated electricity for the state of Georgia is 62% (Georgia Power, 2011). The total imported electricity for the state of Georgia in 2010 is found to be 2.2% (U.S. Energy Information Administration 2011). The import rate was used as a proxy for the percentage of electricity used in the study area that was generated by coal-fired power plants in 2011 because U.S. EIA (Energy Information Administration) had not been updated with 2011 data at the time the analysis. Subtracting the import percentage from the estimates by Power Profiler and Georgia Power suggests that between 50% and 59.8% of electricity comes from coal for the study area. For this study, the conservative lower bound of fifty percent is used.

Arc GIS v.10 is used to locate all power plants in and around the eGRID sub-region south -SRSO. The Sub-Region SRSO covers Georgia, Florida, Alabama and Mississippi (U.S. Environmental Protection Agency 2011d). Only, coal-fired power plants were used to calculate the health care cost generated by the electricity consumption in the study area.

Three buffer bands of 50,100, and 150 miles are used to locate coal-fired power plants near the study area. There are 4, 8, and 13 coal-fired power plants with in a 50, 100, and 150 mile buffer around the study area within SRSO eGRID sub-region, out of which 4, 7, and 9 plants are in Georgia, respectively. The health care costs from other coal-fired power plants within the region but outside the Georgia, such as the W S Lee Plant of South Carolina, were not included in the analysis.

One reason is that the state of Georgia has imported only 2.2% of its electricity in year 2010 and in general, state of Georgia compensates for the occasional additional demand from Alabama plants because they are in the same grid as Georgia (The Atlanta Journal-Constitution 2009). The health care damage is limited to Georgia power plants in the analysis. Figure 3.5 lists all the power plants in and around state of Georgia.

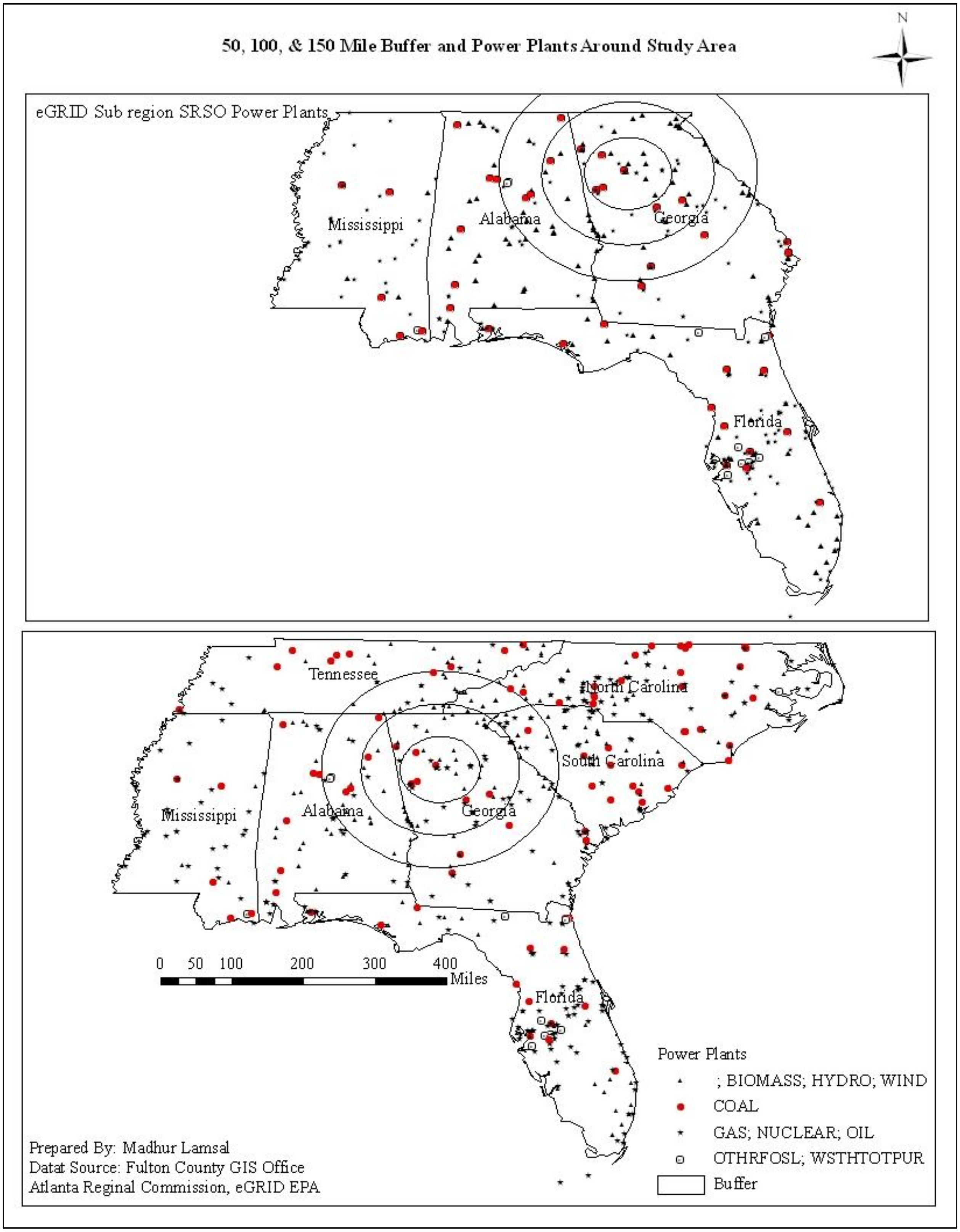

Figure 3.5: eGRID Sub-region Power Plant Location

3.9 Green Roof: Cost Calculation

3.9.1 Energy Benefit

Buildings accounted for 72% of total U.S. electricity consumption in 2006 and this number will rise to 75% by 2025 (U.S Department of Energy 2006). Out of total energy consumption, an average of 35% goes to cooling and heating. 35% of total energy costs were computed to find cooling and heating expenditures for each building. An extensive green roof can reduce room temperature by 5.4-7.2 ^{0}F in a city with average annual temperature of 77-86^{0}F (Peck, 1999). However, this reduction will depend on number of the floors in the building. Therefore, a sensitivity analysis was performed on the reduction in energy consumption due to green roof installation using three methods from the three literatures.

Method 1: Dunnett and Kingsbury (2008) estimate that every decrease in internal building air temperature of 0.9^{0}F can reduce electricity use for air-conditioning up to 8%. Based on the mean reduction of 6.8^{0}F from Peck (1999), a green roof could generate up to 28% reduction in energy use for air-conditioning. So, for Method 1, a twenty-eight present reduction in total cooling and heating costs are computed as the energy benefit.

Method 2: Clark, et al. (2008) estimated 51% of total energy costs could be saved with green roofs in the Ann Arbor, Michigan study area. For Method 2, a fifty-one percent reduction in total energy costs is calculated as energy benefit.

Method 3: In Washington, D.C. Nui, et al. (2010) estimated 10% of total energy costs could be saved with green roofs. Ten percent of total energy cost is calculated as energy benefits in Method 3.

In addition to the three methods described above, four different floors energy-saving scenario were examined. The first scenario assumes that the green roof reduces energy demand up to four floors below the green roof. The second scenario assumes energy benefits for up to three floors below the roof top; scenario 3 counts two floors below the green roof, and, the fourth includes only one floor below the green roof. The four floor scenarios are run for each of the three methods for accounting energy benefits, leading to 12 separate analyses.

3.9.2 Stormwater Benefit

Private stormwater benefit is calculated for each building using the 2010 stormwater ordinance rate as a proxy. Relying on previous studies (Hathaway, et al., 2008, Moran, et al., 2004), it is hypothesized that only 35 % of the proposed fee (0.27/100ft^2) would be imposed on buildings with green roofs. The remaining 65 % can be saved, which counts as the private stormwater benefit.

3.10 Public Benefit with Green Roof

3.10.1 Stormwater Benefit

Bluestone (2010) has estimated that the city of Atlanta will spend $3.2-$5.5 billion dollars in storm water management from 2010 to 2030 under its current building conditions. Using this expenditure schedule, yearly costs are computed, which is then divided by the total roof surface area of Atlanta to estimate the cost imposed per m^2 of roof surface area. Using Hathaway and Moran as a basis, it is assumed that sixty five percent of this cost can be saved with a green roof; this will be realized as a reduction in stormwater infrastructure costs.

3.10.2 Direct Health Benefit

Clark, et al. (2008) estimated the public health benefit for greening a 2000 m^2 roof to be between \$890 and 3390 per year. The benefit calculated by Clark et al. (2008) is limited to removal of nitrogen oxide (NO_x) only from the ambient environment because there are not any studies that have quantified the monetary value of health benefit produced by an extensive green roof from removing other pollutants such as SO_2. In this study the average benefit reported by Clark et al. (2008)-\$2140 per year-is used. Because it is limited to benefits related to NO_x removal, the actual health benefit could be considerably higher.

3.10.3 Indirect Benefit Due to Reduction in Plant Operation Hour

All three methods discussed above found that the annual consumption of energy will decrease with the green roofing scenario. The drop in energy demand due to the green roofs can reduce operational hours of coal-fired power plants. Across all three methods, the eGRID emissions rate of pollutants per kilowatt electricity produced and annual marginal damage per ton of NO_x, SO_2, and CO_2 by Muller et al. (2007) are used to estimate the avoided health care cost by avoided by reducing coal-fired power plant operations.

3.10.4 Benefit Due to UHIE reduction

Replying on Lipton et al. (2004), greening 100% of rooftops in one commercial or industrial neighborhood could reduce that neighborhood's UHIE by 50-90%. It is assumed that on average of 70% of the UHIE energy cost can be saved in the 138 building green roofing scenario.

A 3^0F reduction of the UHIE was assumed and annual kilowatt reduction is estimated. The eGRID emissions rate of pollutants per kilowatt electricity produced and annual marginal damage per ton of NO_x, SO_2 and CO_2 by Muller et al. (2007) is used to estimate the additional avoided health care cost by reducing coal-fired power plant operation due to a drop in the UHIE.

3.11 Discounting of Benefit Cost Flow and Scenario Analysis

It has been estimated that one roof cycle for conventional and green roofs equals 20 and 40 years, respectively (Clark et.al, 2008). After establishing costs and benefits on an annual basis, both the private and public net present value (NPV) of one green roof cycle (40) is calculated. The roof installations occur at year zero for conventional and green roofs; at year 20 a new conventional roof is installed. A discount rate of 4% was applied.

The private net present value (NPV_{PR}) of a green roof is used to determine whether a green roof is beneficial from a private perspective – considering only the costs the building owner would incur and the benefits they would acquire. For buildings with NPV_{PR} greater than zero, the owners should adopt a green roof irrespective of the potential social costs or benefits of doing so. That is, the private welfare of owners of buildings with NPV_{PR} greater than zero would increase if they were to adopt a green roof.

The public net present value (NPV_{PU}) accounts for all of the public costs and benefits of a green roof, net of the public costs and benefits of a conventional roof, but does not account for the private costs and benefits. The social net present value (NPV_S) is the sum of NPV_{PR} and NPV_{PU}. Social welfare would increase if all buildings with NPV_S greater than zero adopt a green roof. It is, therefore, in society's interest to encourage the adoption of green roofs on buildings where NPV_S is positive, even if NVP_{PR} for that building is negative.

3.12 Economic Analysis of Positive Externality

Vegetation helps to cool the ambient air around it by the process of evapotranspiration. Therefore, it can be assumed that installing a green roof can influence ambient air temperature, thereby reducing a neighboring building's energy use. This can create an opportunity for a neighbor to enjoy a cost-free benefit due to its proximity to the green roof. In other words, if installing a green roof generates a positive externality, buildings in the neighborhood may be able to free-ride on it. Depending on the magnitude of the positive externality, the private green roof adoption decision of a neighbor may be affected. The magnitude and scope of ambient air cooling, however, is highly uncertain.

To explore the potential influence of green roof-induced ambient air cooling on the private green roof adoption decision a new dimension is added to the analysis. Using the parameter estimates from Akbari et al. (1992), the effect of ambient air cooling on the private and social costs and benefits of adopting a green roof are estimated for each building in the study area. A range of 1^0F to 6^0F ambient cooling is explored, and buildings for which the privately and/or socially optimal roof type changes due to the positive externality are identified. This is done using two separate modeling frameworks.

The first framework models the ambient cooling as an aggregate effect from the adoption of green roofs on all 138 buildings studied. The marginal cooling effect of any one building, however, is assumed to be negligible. By comparing the private net present value of a green roof in the absence of a cooling effect (NVP_{PR}^0) to the private net present value with the cooling effect (NVP_{PR}^1 through NVP_{PR}^6, where the superscript represents the number of degrees F of ambient cooling), potential freeriders can be identified. That is, a building where $NVP_{PR}^0 > 0$

and $NVP_{PR}^1 < 0$ would adopt a green roof in the absence of an aggregate cooling effect but would not adopt in the presence of a 1^0F aggregate cooling effect. Such a building would, from a private perspective, be better off freeriding on the cooling effect. The question then arises, "Would it be socially optimal for such a building to adopt a green roof in the presence of the aggregate cooling effect?" The answer to that question would be "yes" if $NPV_S^1 > 0$, and "no" otherwise.

The second framework models the ambient cooling effect on a building-by-building basis, as a function of the surface area of the building's roof. The ambient cooling effect is highest at the edge of the roof and decays according to equation 3.4 away from the roof edge. The rate of cooling effect buffer follows an exponential decay change.

$$Cooling\_Buffer = A_0 e^{-\lambda t} \qquad 3.4$$

Where, A_0 represents area of green space, lambda (λ) represents cooling effect decay constant, and t as quantity at time t, which was kept constant 1. The actual magnitude of decay constant (λ) is highly uncertain for green roof vegetation. Larger decay constant make the cooling effect vanish much more rapidly.

In this framework, the positive externality one building enjoys depends on its proximity to the building generating it. Additionally, the scope of the positive externality generated is monotonically increasing in the surface area of the roof. So, a green roof adopter with a large roof will generate a relatively large positive externality for its closest neighbors. This framework can address a number of questions:

1) What parameterization of the decay function would lead to free riding?

2) Is the parameterization that would induce free riding realistic?

3) For which buildings would it be socially optimal to adopt a green roof?

3.13 Subsidy Analysis

Green spaces such as green roofs have private as well social benefits. The social benefit is realized in the form of ambient air cooling, reduced energy demand, and reduced health care cost and sustainable storm water management. Green roofing is an action of an agent that produces many positive effects in a society. Therefore, such a behavior should be incentivized. However, deciding efficient structure of subsidy/incentive is often contentious task. This research tested three incentive/subsidy structures to quantify the number of buildings and their spatial location that can be ideal candidate for such incentives. Following three logical tests were performed.

1. Only those building with private benefit less than 0 and social benefit greater than 0.
2. Only those buildings with net private benefit greater than 0.
3. Those buildings with highest public benefit with green roof over difference of installation and maintenance cost of conventional and green roofs.

This research utilizes the incentive program adopted by city of Portland, Oregon for green roof promotion. The program is called “Grey to Green”, that reimburse $5 per square foot ($53.82/m^2) of green roof installed within the city limit of Portland (Portland Bureau of Environmental Services 2012). The research used the Portland rate to screen that out of privately and socially optimal green roofs, which will still be beneficial for the city of Atlanta after paying the incentives.   The rate (53.82/m^2) is used as proxy to quantify the cost-benefit if green roof are suggested to the privately and socially optimal roofs that generate higher benefit than the incentive reimbursed.

CHAPTER 4

ECONOMIC ANALYSIS & RESULTS

4.0 Introduction: Scenario Analysis

The results are organized by scenarios. Three distinct components define a scenario: the green roof installation and maintenance cost, and energy savings method; the number of floors of energy savings; and the reduction in the urban heat island effect. The three cost methods are designated M1, M2, and M3. M1 uses the cost parameters from Carter et al. (2008), M2 uses the parameters from Clark et al. (2008), and M3 use the parameters from Nui et.al (2010). F1, F2, F3, and F4 are used to designate whether 1 floor, 2 floors, 3 floors, or 4 floors of energy savings are considered. H0 through H6 represent the number of degrees F of ambient cooling are modeled. In total there are 84 scenarios, referred to as M1F1H0 through M3F4H6. Costs and benefits of adopting conventional and green roofs are calculated on an annual basis, adjusted to 2011 constant dollars using consumer price index for average urban region (Federal Reserve Bank of Minneapolis 2011), and aggregated over a 40-year green roof cycle.

4.1 Four-Floor Energy Benefits (F4) and No Urban Heat Island Mitigation (H0)

In this section, the results from Scenarios M1F4H0, M2F4H0 and M3F4H0 are presented. These results include the estimates of NVP_{PR} and NPV_{S} on a building-by-building basis, as well as the aggregate NPV_{PR} (NPV_{S}) for the study area, assuming all buildings adopt the privately (socially) optimal roof type. A discussion of the factors driving the differences across the three methods is also included.

4.1.1 M1F4H0 Results

Green roof adoption is optimal from a private perspective for 42 out of the 138 buildings considered in the study area (see Figure 4.1). NPV_{PR} ranges from a little less than $60,000 over the life of the green roof to -$1 million. Table 4.1 presents descriptive statistics for NPV_{PR} associated with M1F4H0. Looking at Figure 4.1, there is no obvious spatial dimension to the optimal roof type – green roofs and conventional roofs are distributed throughout the study area. Furthermore, there is no obvious correlation between roof size and optimal roof type.

Socially, there are 63 buildings that are optimal from a social perspective out of 138 buildings considered in the study area (See Figure 4.2). NPV_S ranges from a little more than $186,000 over the life of the green roof to -$ 616,000. Table 4.2 presents descriptive statistics for NPV_S associate with M1F4H0

Figure 4.1: Private NPV Building-by-Building under M1F4H0

Table 4.1: Private Descriptive Statistics M1F4H0

M1F4H0	GR_{PR}	GR_{PR} per m^2
Mean	-$49,387	-$26.12
Standard Error	$9,844	$4.17
Median	-$23,367	-$27.12
Std. Dev.	$115,641	$49.00
Minimum	-$1,013,407	-$111.87
Maximum	$59,940	$141.93
Sum	-$6,815,413	-$3,604.36
Corr. Coef. (roof area v. GR_{PR} and GR_{PR}/m^2)	-0.6865	-0.0589
Number of Roofs	138	
Beneficial with GR	42	
Not Beneficial with GR	96	

Figure 4.2: Social NPV Building-by-Building under M1F4H0

Table 4.2: Social Descriptive Statistics M1F4H0

M1F4H0	GR_S	GR_S per m^2
Mean	$5,102	$3.00
Std. Error	$7,452	$4.38
Median	$10,041	$5.90
Std. Dev.	$87,538	$51.42
Minimum	-$616,343	-$362.04
Maximum	$186,576	$109.60
Corr. Coef. (roof area v. GR_S and GR_S/m^2)	-0.28	-0.06
Sum	$704,076	$413.58
Number of Roofs	138	
Beneficial with GR	63	
Not Beneficial with GR	75	

4.1.2 M2F4H0 Results

Green roof adoption is optimal from a private perspective for 119 out of the 138 buildings considered in the study area (see Figure 4.3) NPV_{PR} ranges a little more than $1.2 million over the life of green roof to -$92,712. Table 4.3 present the descriptive statistics for NPV_{PR} associated with M2F4H0. Looking at Figure 4.3, there is spatial dimension to the optimal roof type- larger the roof size greater the benefit is. The correlation coefficient is also found to be positive (See Table 4.3).

Socially, there are 135 buildings that are optimal for from social perspective out of 138 buildings considered in the study area (See Figure 4.4). The NPV_S ranges from little more than $1.5 million over the life of the green roof to -$34423. Table 4.4 presents descriptive statistics for NPV_S associated with M2F4H0. Looking at the figure, there is obvious spatial dimension to the optimal roof type-green roofs are favorable over conventional roof. The correlation coefficient is also found to be positive (See Table 4.4).

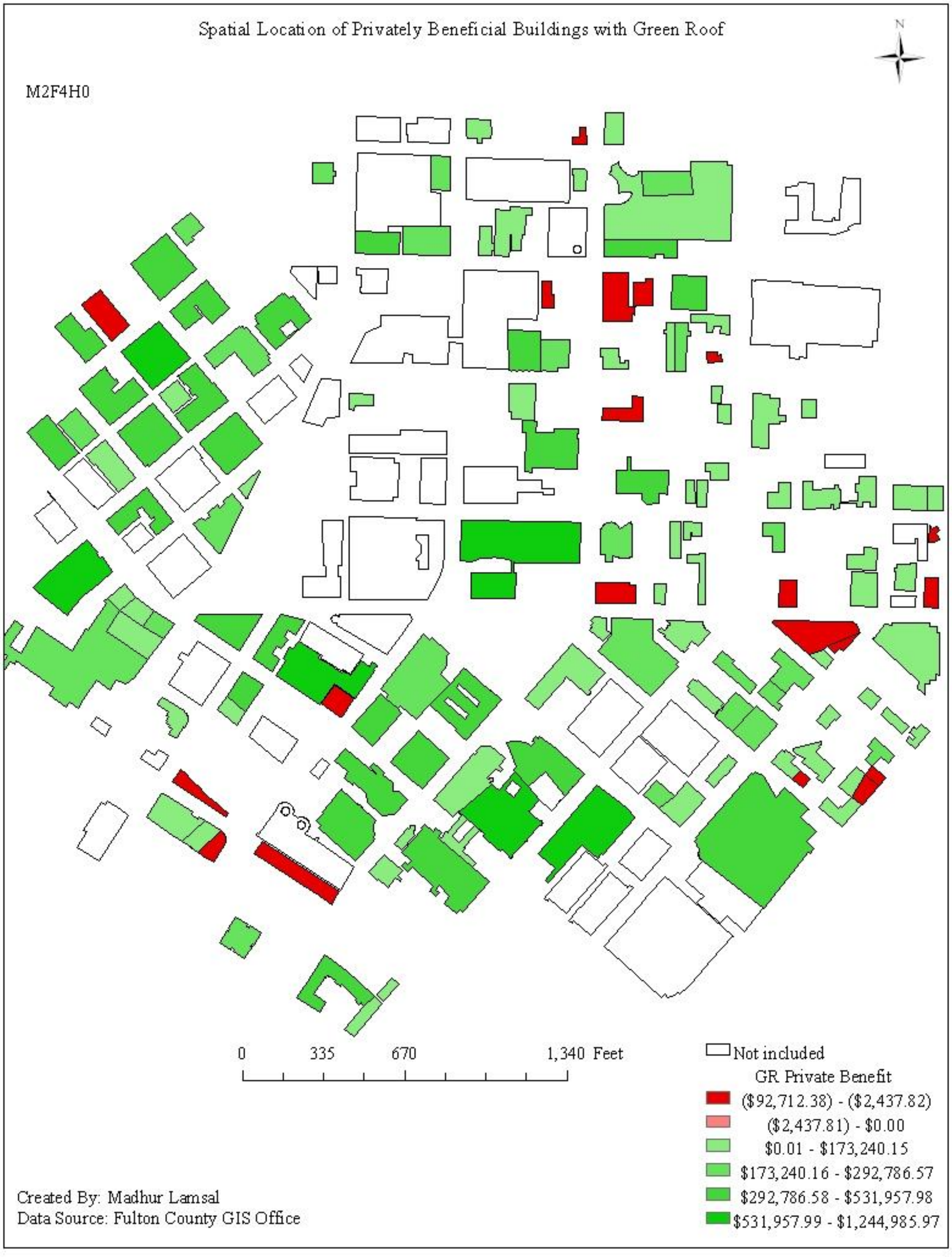

Figure 4.3: Private NPV Building-by-Building under M2F4H0

Table 4.3: Private Descriptive Statistics M2F4H0

M2F4H0	GR_{PR}	GR_{PR} per m^2
Mean	$170,800	$105.62
Standard Error	$16,516	$7.63
Median	$121,580	$103.79
Std. Dev.	$194,024	$89.61
Minimum	-$92,712	-$51.20
Maximum	$1,244,986	$412.91
Sum	$23,570,450	$14,574.90
Corr. Coef. (roof area v. GR_{PR} and GR_{PR}/m^2)	0.6099	-0.0589
Number of Roofs	138	
Beneficial with GR	119	
Not Beneficial with GR	19	

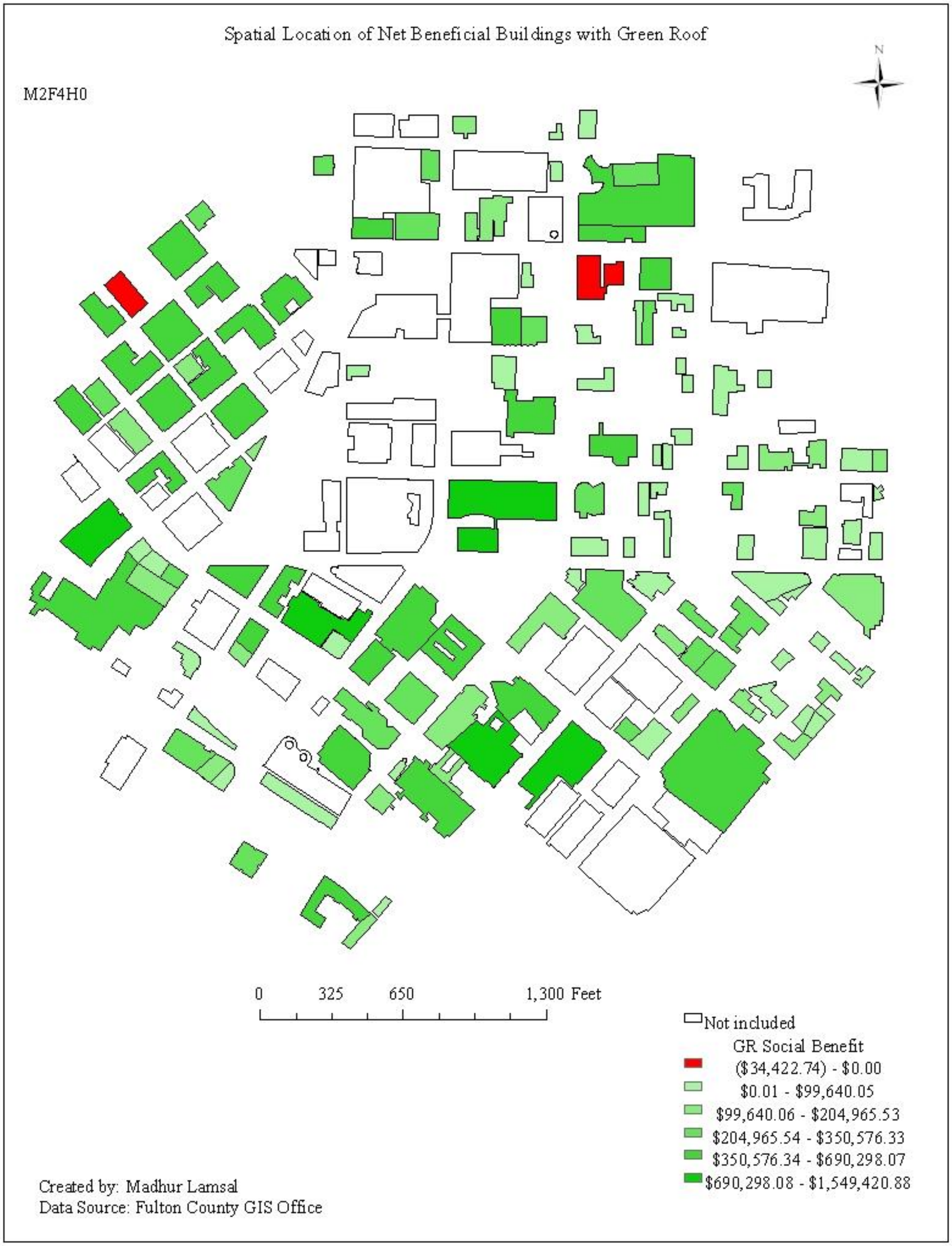

Figure 4.4: Social NPV Building-by-Building under M2F4H0

Table 4.4: Social Descriptive Statistics M2F4H0

M2F4H0	GR_S	GR_S per m^2
Mean	$225,548	$132.49
Std. Error	$19,729	$11.59
Median	$158,983	$93.39
Std. Dev.	$231,768	$136.14
Minimum	-$34,423	-$20.22
Maximum	$1,549,421	$910.13
Sum	$31,125,584	$18,283.25
Corr. Coef. (roof area v. GR_S and GR_S/m^2)	0.75	-$0.06
Number of Roofs	138	
Beneficial with GR	135	
Not Beneficial with GR	3	

4.1.2 M3F4H0 Results

There are only 7 buildings that are optimal for green roof adoption from a private perspective out of 138 buildings considered in the study area (See Figure 4.5). NPV_{PR} ranges little more than $10,000 to -$623,297 over the life of the green roof. Table 4.5 presents descriptive statistics for NPV_{PR} associated with M3F4H0. Looking at Figure 4.5, it is clear that conventional roofs are favorable over green roofs.

Socially, there are 73 buildings that are optimal from a social perspective out 138 building considered in the study area (See Figure 4.6). NPV_S ranges from a $60,000 to -$227,597 over the life of the green. Table 5.6 presents descriptive statistics NPV_S. Looking at Figure 4.6, it is clear that as social benefits are added, green roofs are beneficial for some clusters of buildings.

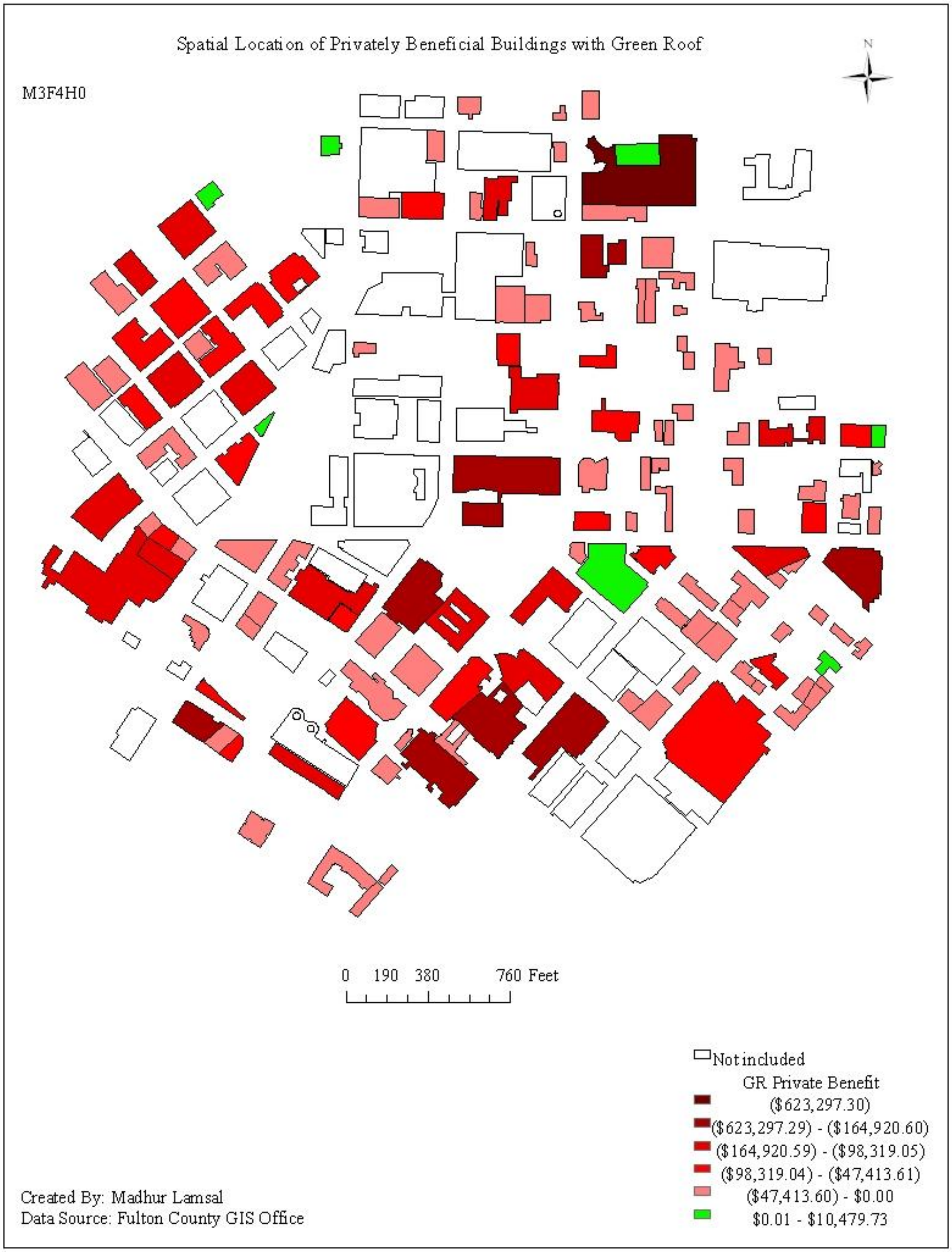

Figure 4.5: Private NPV Building-by-Building under M3F4H0

Table 4.5: Private Descriptive Statistics M3F4H0

M3F4H0	GR_{PR}	GR_{PR} per m^2
Mean	-53,498	-$30.39
Standard Error	6,060	$1.49
Median	-31,076	-$30.75
Std. Dev.	71,188	$17.50
Minimum	-623,297	-$61.02
Maximum	10,480	$29.63
Sum	-7,382,766	-$4,194.13
Corr. Coef. (roof area v. GR_{PR} and GR_{PR}/m^2)	-0.9067	-0.0589
Number of Roofs	138	
Beneficial with GR	7	
Not Beneficial with GR	131	

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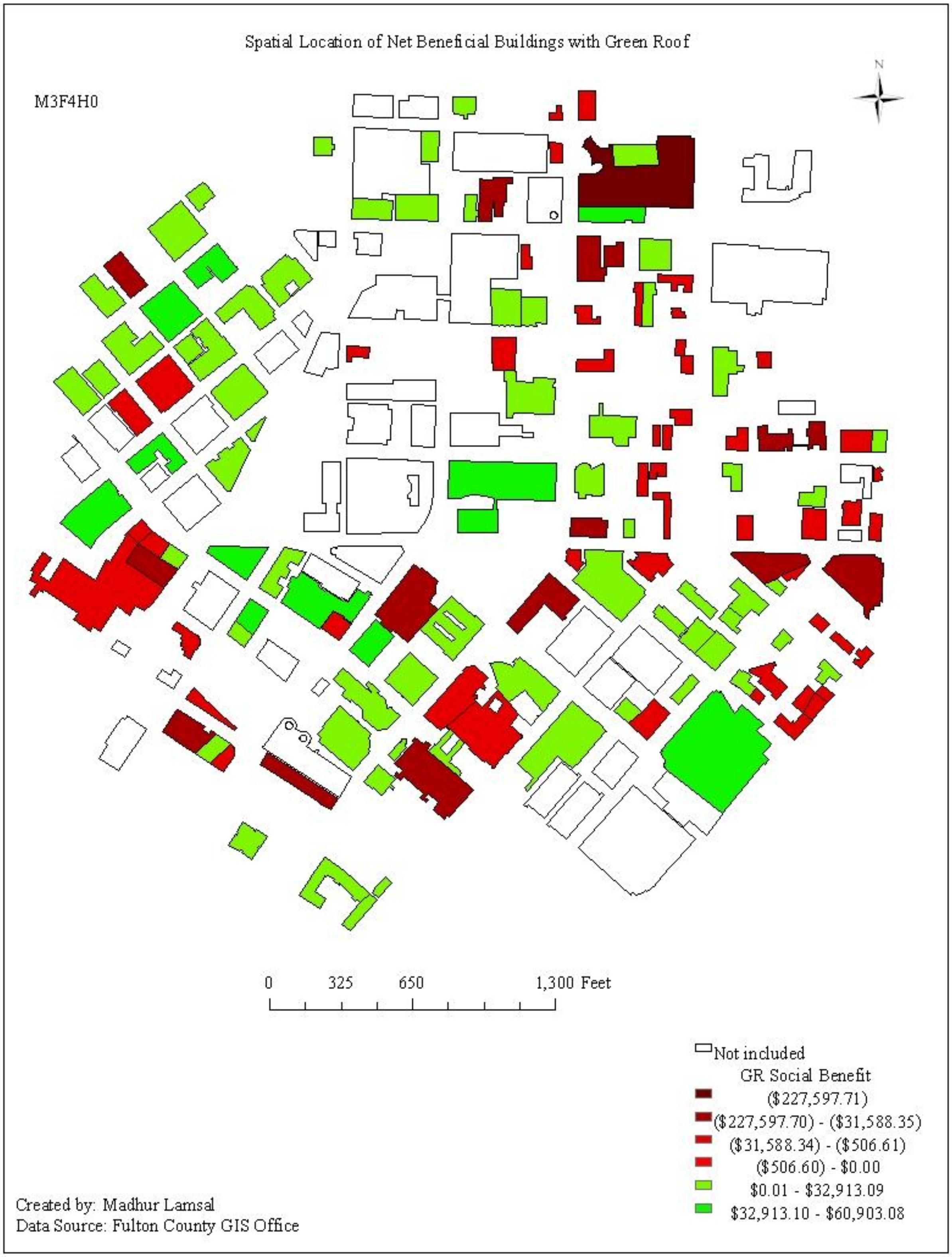

Figure 4.6: Social NPV Building-by-Building under M3F4H0

Table 4.6: Social Descriptive Statistics M3F4H0

M3F4H0	GR_S	GR_S per m^2
Mean	$796.53	$0.47
Std. Error	$2,687.29	$1.58
Median	$2,298.28	$1.35
Std. Dev.	$31,568.50	$18.54
Minimum	-$227,597.71	-$133.69
Maximum	$60,903.08	$35.77
Sum	$109,921.37	$64.57
Corr. Coef. (roof area v. GR_S and GR_S/m^2)	-0.31	-0.06
Number of Roofs	138	
Beneficial with GR	73	
Not Beneficial with GR	65	

Across the three methods, M2[3] leads to the highest number of buildings for which a green roof is the optimal type. This is true when looking at both NPV_{PR} and NPV_S. One reason is that M2 assume 51% of energy saving per floor, which is the highest benefit scenario across the three methods.

Among the other two methods, the number of privately optimal green roofs is higher for M1[4] but the number of socially optimal green roofs is higher for M3[5]. The difference of installation cost of conventional and green is $71.63 and $67.00 across M1 and M3. The difference contributed to turn higher social optimal green roofs under M3.

[3] Recall that M2 represents the installation and maintenance costs, and energy savings using the parameters from Clark et al. (2008).

[4] Recall that M1 represents the installation and maintenance costs, and energy saving using parameters from Carter el al. (2008)

[5] Recall that M3 represents the installation and maintenance costs, and energy saving using parameters from Nui et al. (2010)

4.2 Three-Floor Energy Benefits (F3) and No Urban Heat Island Mitigation (H0)

In this section, the results from Scenarios M1F3H0, M2F3H0 and M3F3H0 are presented. These results include the estimates of NVP_{PR} and NPV_{S} on a building-by-building basis, as well as the aggregate NPV_{PR} (NPV_{S}) for the study area, assuming all buildings adopt the privately (socially) optimal roof type. A discussion of the factors driving the differences across the three methods is also included.

4.2.1 M1F3H0 Results

There are only 14 buildings that are optimal for green roof adoption from a private perspective out of 138 buildings considered in the study area (See Figure 4.7). NPV_{PR} ranges little more than $26,000 to -$1 million over the life of the green roof. Table 4.7 presents descriptive statistics for NPV_{PR} associated with M3F4H0. Looking at Figure 4.7, it is clear that conventional roofs are favorable over green roofs.

Socially, there are 52 buildings that are optimal from a social perspective out 138 building considered in the study area (See Figure 4.8). NPV_{S} ranges from a $60,000 to 227,597 over the life of the green. Table 5.6 presents descriptive statistics NPV_{S}. Looking at Figure 4.8, if social benefits are accounted, green roofs are beneficial for some clusters of buildings.

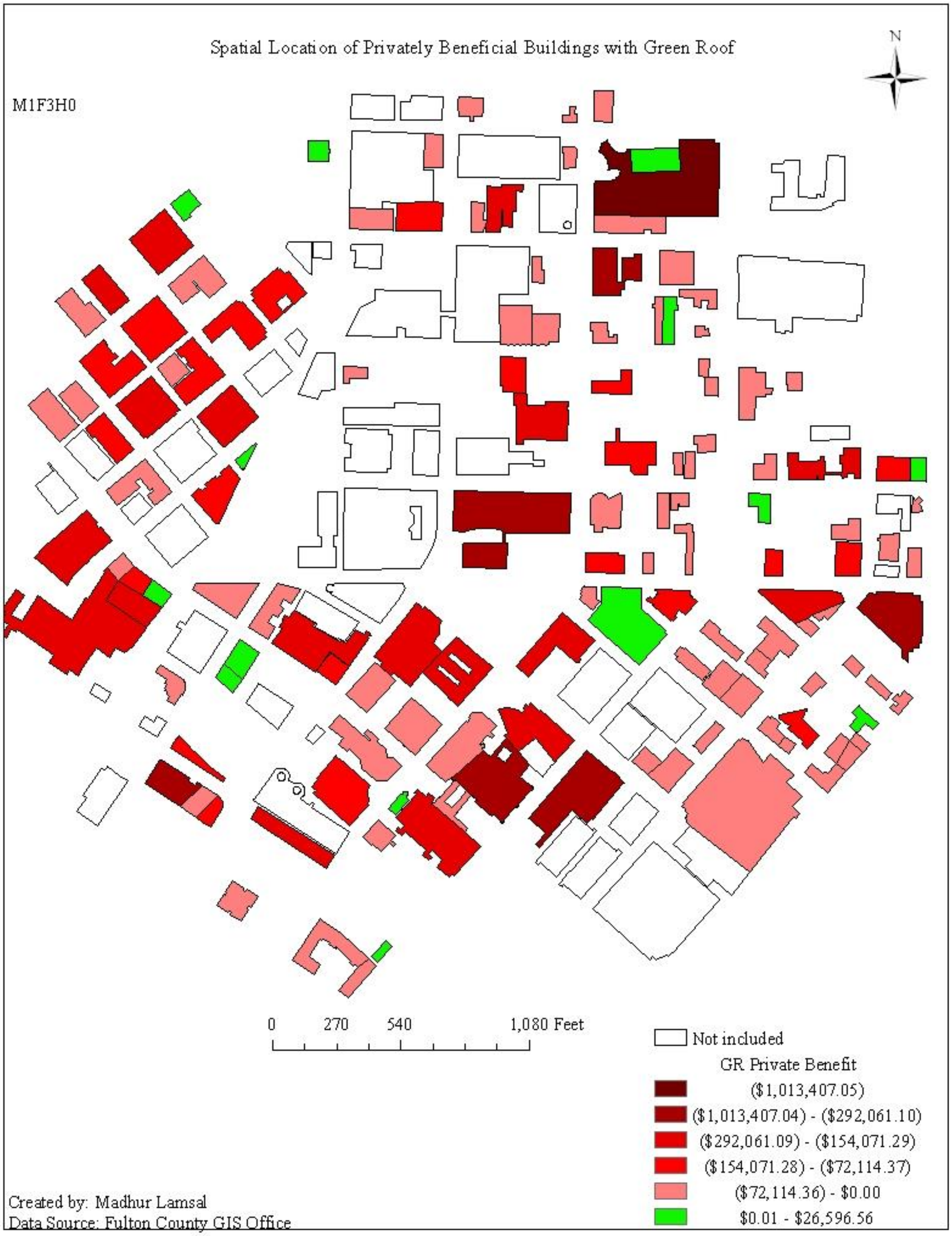

Figure 4.7: Private NPV Building-by-Building under M1F3H0

Table 4.7: Private Descriptive Statistics M1F3H0

M1F3H0	GR_{PR}	GR_{PR} per m^2
Mean	-$80,173	-$42.55
Standard Error	$9,948	$2.86
Median	-$42,251	-$45.44
Std. Dev.	$116,858	$33.64
Minimum	-$1,013,407	-$111.87
Maximum	$26,597	$75.19
Sum	-$11,063,895	-$5,872.35
Corr. Coef. (roof area v. GR_{PR} and GR_{PR}/m^2)	-0.8942	-0.1347
Number of Roofs	138	
Beneficial with GR	14	
Not Beneficial with GR	124	

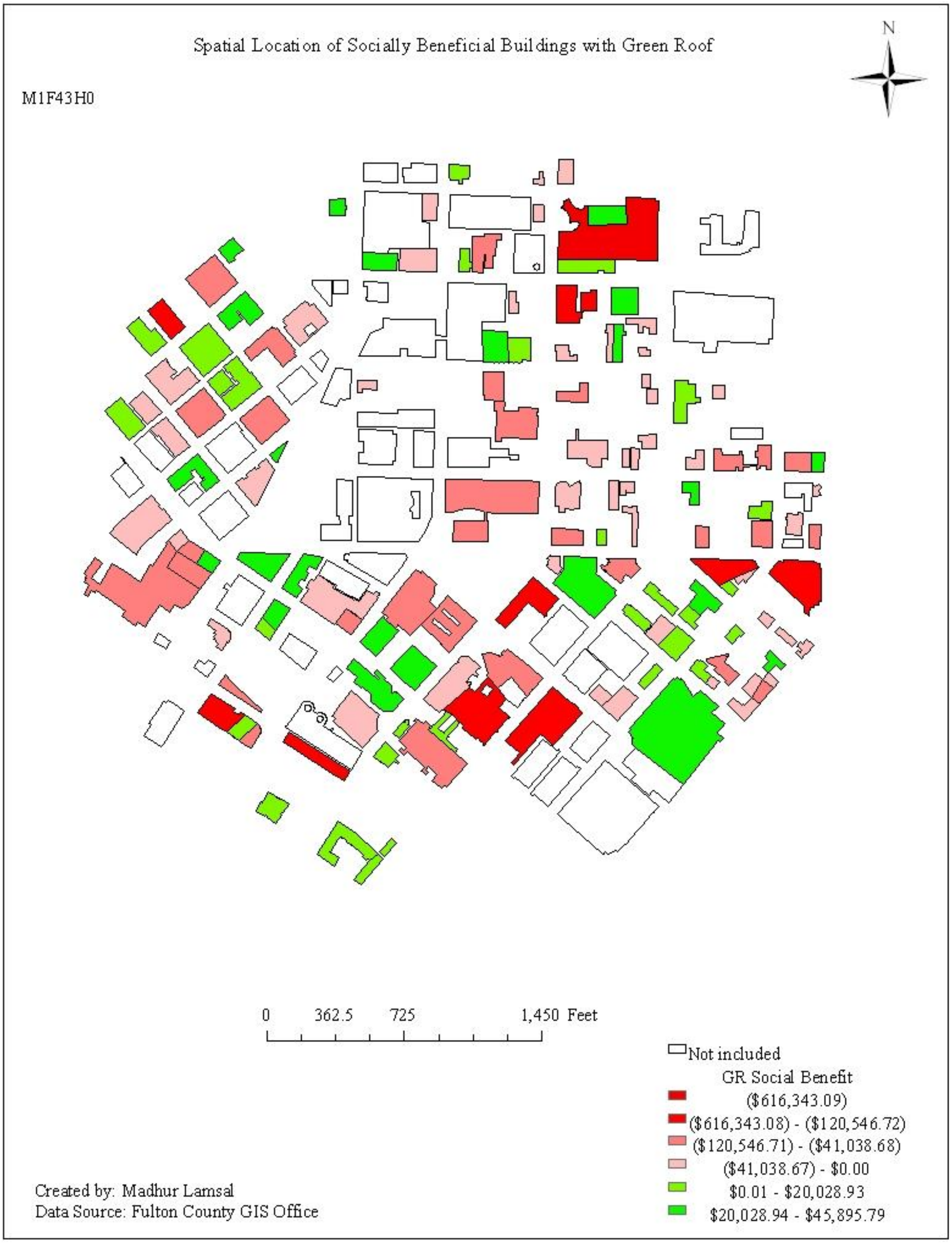

Figure 4.8: Social NPV Building-by-Building under M1F3H0

Table 4.8: Social Descriptive Statistics M1F3H0

M1F4H0	GR_S	GR_S per m^2
Mean	-$25,727	-$15.11
Std. Error	$6,133	$3.60
Median	-$9,410	-$5.53
Std. Dev.	$72,045	$42.32
Minimum	-$616,343	-$362.04
Maximum	$45,896	$26.96
Corr. Coef. (roof area v. GR_S and GR_S/m^2)	-0.69	-0.14
Sum	-$3,550,258	-$2,085.43
Number of Roofs	138	
Beneficial with GR	52	
Not Beneficial with GR	86	

4.2.2 M2F3H0 Results

Green roof adoption is optimal from a private perspective for 119 out of the 138 buildings considered in the study area (see Figure 4.3) NPV_{PR} ranges a little more than $750,000 over the life of green roof to -$92,712. Table 4.9 present the descriptive statistics for NPV_{PR} associated with M2F3H0. Looking at Figure 4.9, there is spatial dimension to the optimal roof type- larger the roof size greater the benefit is.

Socially, there are 135 buildings that are optimal for from social perspective out of 138 buildings considered in the study area (See Figure 4.10). The NPV_S ranges from little more than $1 million over the life of the green roof to -$34,423. Table 4.10 presents descriptive statistics for NPV_S associated with M2F4H0. Looking at the figure, there is obvious spatial dimension to the optimal roof type-green roofs are favorable over conventional roof.

Figure 4.9: Private NPV Building-by-Building under M2F3H0

Table 4.9: Private Descriptive Statistics M2F3H0

M2F3H0	GR_{PR}	GR_{PR} per m^2
Mean	$114,506	$75.56
Standard Error	$10,216	$5.24
Median	$93,550	$70.29
Std. Dev.	$120,009	$61.52
Minimum	-$92,712	-$51.20
Maximum	$754,700	$290.86
Sum	$15,801,798	$10,427.73
Corr. Coef. (roof area v. GR_{PR} and GR_{PR}/m^2)	0.6037	-0.1347
Number of Roofs	138	
Beneficial with GR	119	
Not Beneficial with GR	19	

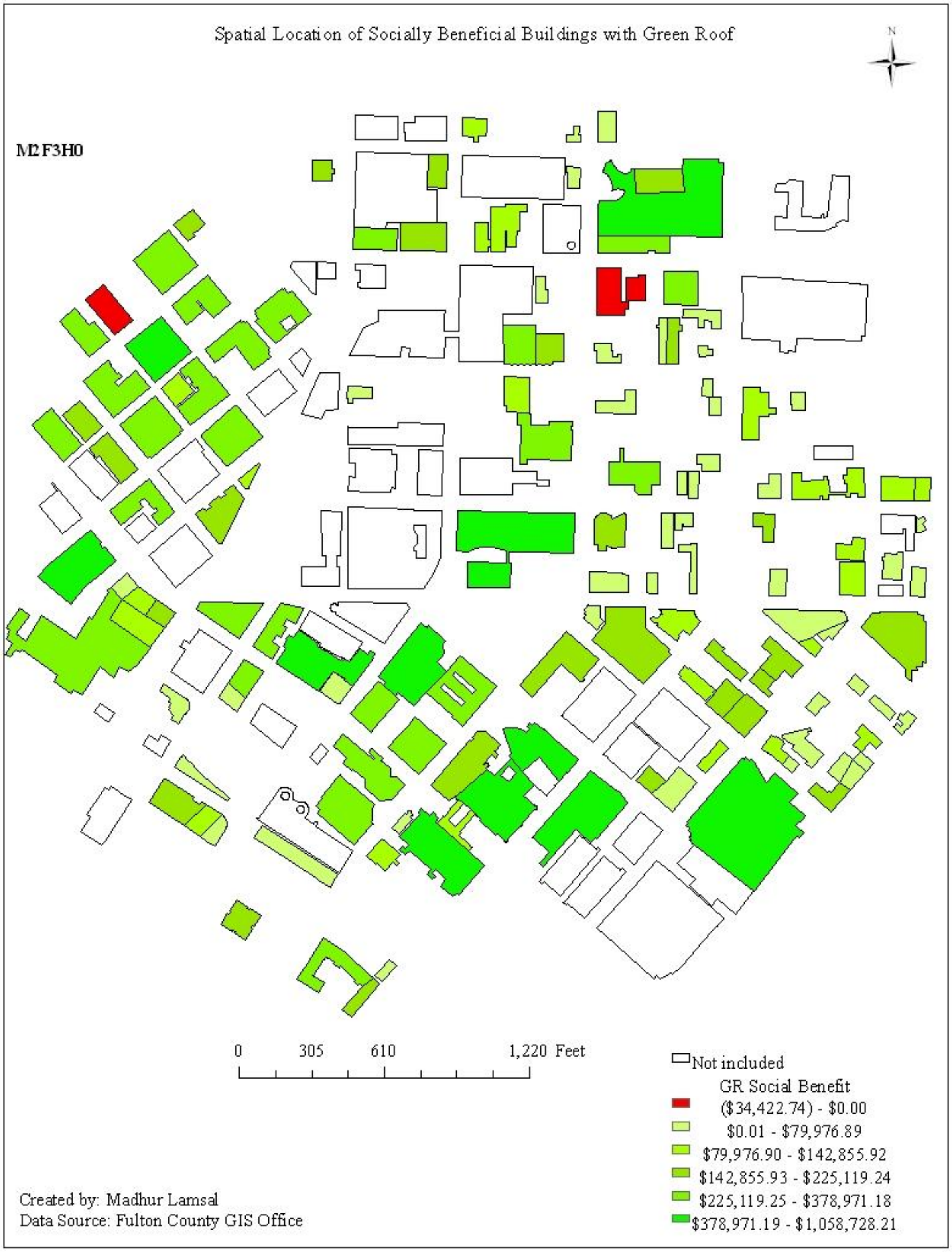

Figure 4.10: Social NPV Building-by-Building under M2F3H0

Table 4.10: Social Descriptive Statistics M2F3H0

M2F3H0	GR_S	GR_S per m^2
Mean	$169,174	$99.37
Std. Error	$13,565	$7.97
Median	$129,700	$76.19
Std. Dev.	$159,358	$93.61
Minimum	-$34,423	-$20.22
Maximum	$1,058,728	$621.90
Sum	$23,346,076	$13,713.54
Corr. Coef. (roof area v. GR_S and GR_S/m^2)	0.80	-0.14
Number of Roofs	138	
Beneficial with GR	135	
Not Beneficial with GR	3	

4.2.3 M3F3H0 Results

There is only one building that is optimal for green roof adoption from a private perspective out of 138 buildings considered in the study area (See Figure 4.11). NPV_{PR} ranges $2,000to -$623,297 over the life of the green roof. Table 4.11 presents descriptive statistics for NPV_{PR} associated with M3F4H0. Looking at Figure 4.11, it is clear that conventional roofs are favorable over green roofs.

Socially, there are 50 buildings that are optimal from a social perspective out 138 building considered in the study area (See Figure 4.12). NPV_S ranges from little more than $15,000 to -$227,597 over the life of the green. Table 4.12 presents descriptive statistics NPV_S. Looking at Figure 4.12, socially some section of study are can benefit with green roofs.

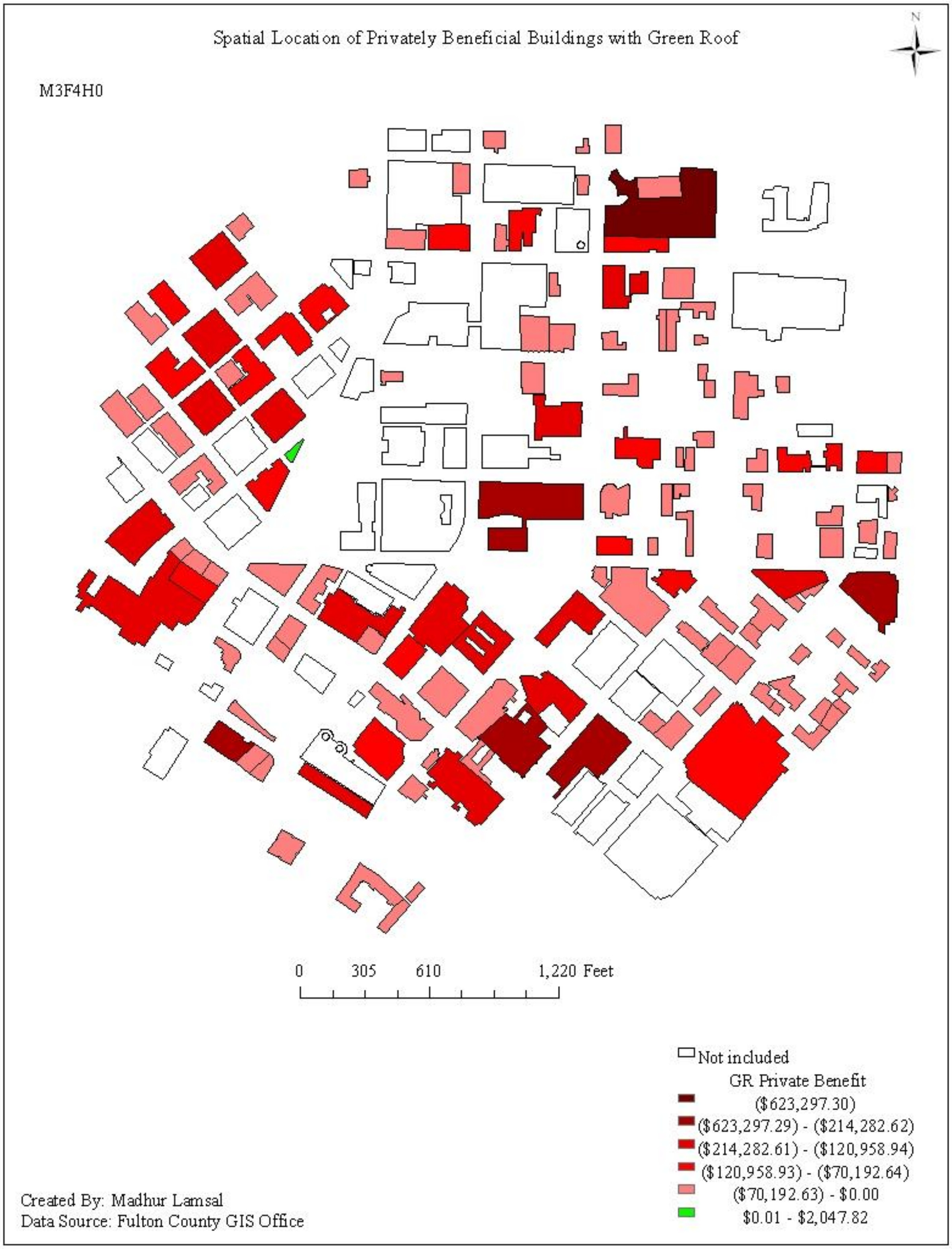

Figure 4.11: Private NPV Building-by-Building under M3F3H0

Table 4.11: Private Descriptive Statistics M3F3H0

M3F3H0	GR_{PR}	GR_{PR} per m^2
Mean	-$64,493	-$36.26
Standard Error	$6,456	$1.02
Median	-$41,763	-$37.29
Std. Dev.	$75,846	$12.02
Minimum	-$623,297	-$61.02
Maximum	$2,048	$5.79
Sum	-$8,900,080	-$5,004.12
Corr. Coef. (roof area v. GR_{PR} and GR_{PR}/m^2)	-0.9692	-0.1347
Number of Roofs	138	
Beneficial with GR	1	
Not Beneficial with GR	137	

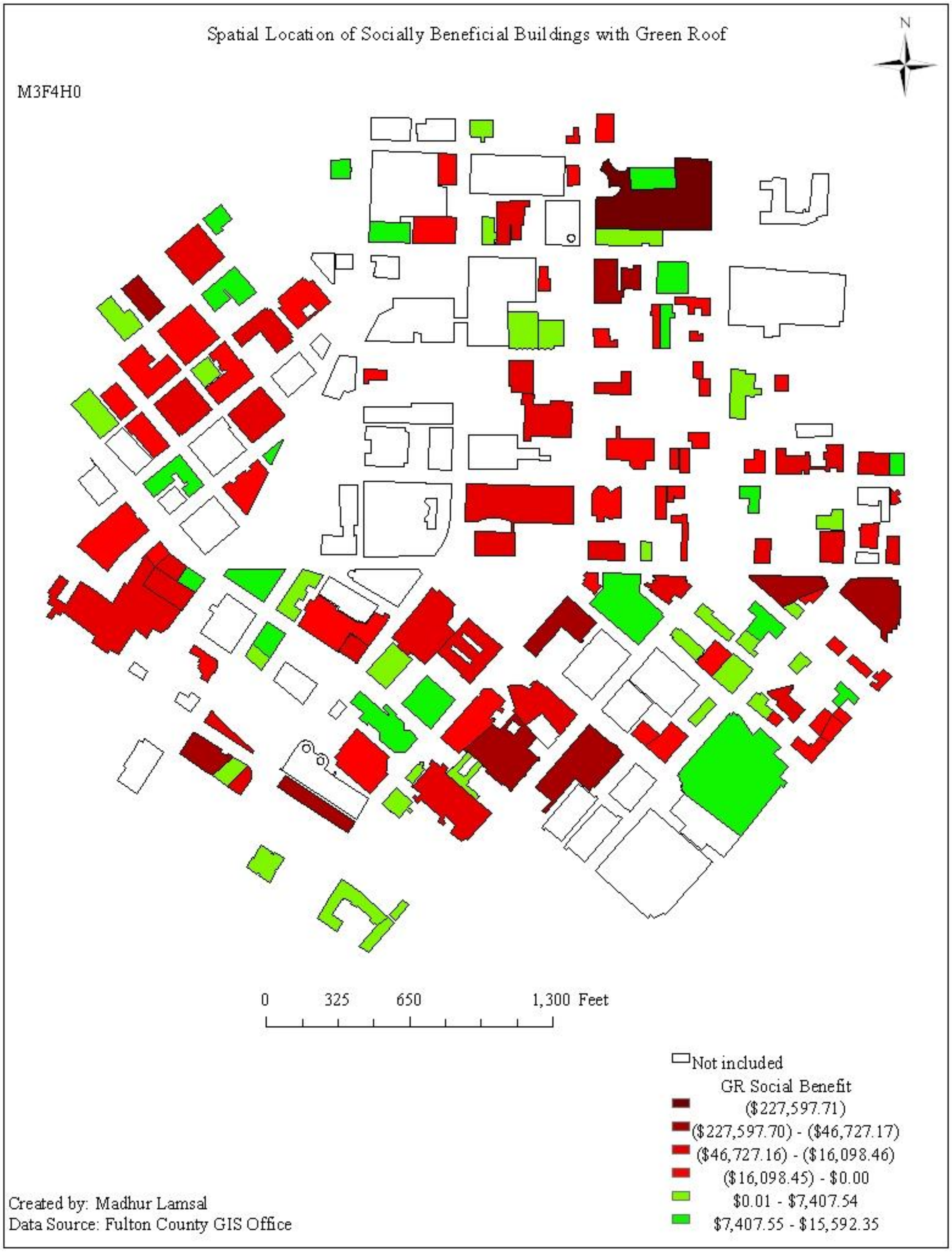

Figure 4.12: Social NPV Building-by-Building under M3F3H0

Table 4.12: Social Descriptive Statistics M3F3H0

M3F4H0	GR_S	GR_S per m^2
Mean	-$10,213.65	-$6.00
Std. Error	$2,251.86	$1.32
Median	-$3,672.28	-$2.16
Std. Dev.	$26,453.32	$15.54
Minimum	-$227,597.71	-$133.69
Maximum	$15,592.35	$9.16
Sum	-$1,409,483.75	-$827.93
Corr. Coef. (roof area v. GR_S and GR_S/m^2)	-0.71	-0.14
Number of Roofs	138	
Beneficial with GR	50	
Not Beneficial with GR	88	

Across the three methods, M2 leads to the highest number of buildings for which a green roof is the optimal type. This is true when looking at both NPV_{PR} and NPV_S. One reason is that M2 assume 51% of energy saving per floor, which is the highest benefit scenario across the three methods.

Among the other two methods, socially M1 and M3 have almost e equal number of optimal green roofs; 52 and 50 respectively. However, M1 has higher optimal green roofs (14) than M3 (1) privately.

4.3 Two and One-Floor Energy Benefits (F2 and F1) and No Urban Heat Island Mitigation (H0)

In this section, the results from Scenarios M1F2H0, M2F2H0, M3F2H0 and M1F1H0, M1F2H0, M1F1H0 are presented. These results include the estimates of NVP_{PR} and NPV_S on a building-by-building basis, as well as the aggregate NPV_{PR} (NPV_S) for the study area, assuming all buildings adopt the privately (socially) optimal roof type. A discussion of the factors driving the differences across the three methods is also included.

4.3.1 M1F2H0 and M1F1H0 Results

There is only one building that is optimal for green roof adoption from a private perspective out of 138 buildings considered in the study area under M1F2H0 (See Figure 4.13). Under M1F1H0, none of building is favorable for green roofs. NPV_{PR} ranges close to 3,000 to -$ 1.2 million over the life of the green roof under F2[6] and F1[7] scenario. Table 4.13 and 4.14 presents descriptive statistics for NPV_{PR} associated with M1F2H0 and M1F1H0. Looking at Figure 4.13, it is clear that conventional roofs are favorable over green roofs.

Socially, there are 6 and 0 buildings that are optimal from a social perspective out 138 building considered in the study area (See Figure 4.14) under M1F2H0 and M1F1H0. NPV_S ranges from little more than $14,000 to -$888,482 over the life of the green. Table 4.15 and 4.16 presents descriptive statistics NPV_S. Looking at Figure 4.14, there are not any spatial locations of building that can benefit with green roofs.

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[6] Recall F2 represents that a green roofs can generate energy benefit up to two floors below the green roofs
[7] Recall F1 represents that a green roors can generate energy benefit only one floors below the green roofs

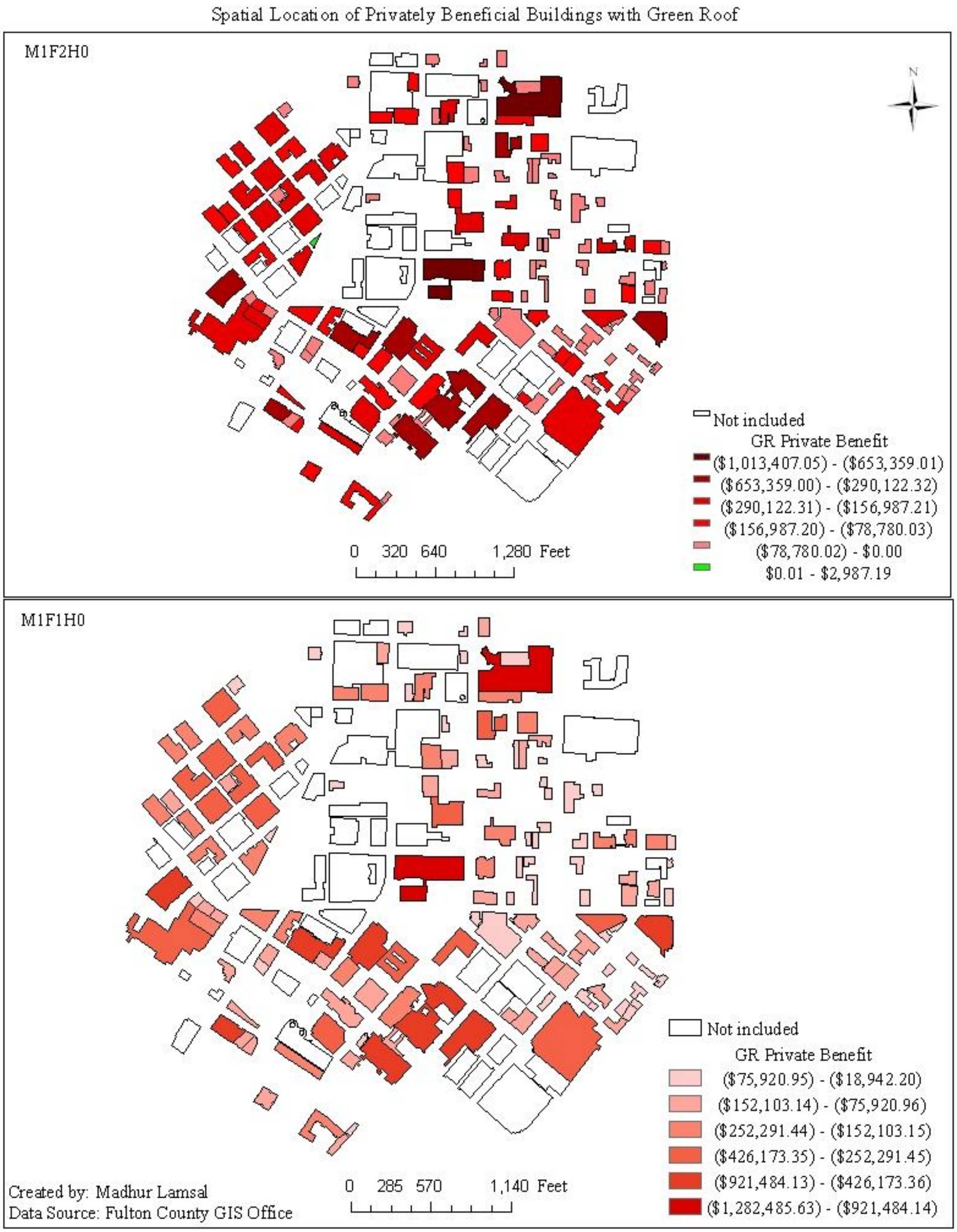


Figure 4.13: Private NPV Building-by-Building under M1F2H0 and M1F1H0

Table 4.13: Private Descriptive Statistics M1F2H0

M1F2H0	GR_{PR}	GR_{PR} per m^2
Mean	-$116,065.11	-68.18
Standard Error	$11,449.08	6.73
Median	-$79,115.68	-46.47
Std. Dev.	$134,496.20	79.00
Minimum	-$1,013,407.05	-595.28
Maximum	$2,987.19	1.75
Sum	-$16,016,985.02	-9,408.42
Corr. Coef. (roof area v. GR_{PR} and GR_{PR}/m^2)	-0.9849	-0.2773
Number of Roofs	138	
Beneficial with GR	1	
Not Beneficial with GR	137	

Table 4.14: Private Descriptive Statistics M1F1H0

M1F1H0	GR_{PR}	GR_{PR} per m^2
Mean	-$162,751.88	-91.99
Standard Error	$14,817.63	0.61
Median	-$106,960.99	-92.64
Std. Dev.	$174,067.77	7.16
Minimum	-$1,282,485.63	-111.87
Maximum	-$18,942.20	-58.30
Sum	-$22,459,759.39	-12,695.21
Corr. Coef. (roof area v. GR_{PR} and GR_{PR}/m^2)	-0.9987	-0.5024
Number of Roofs	138	
Beneficial with GR	0	
Not Beneficial with GR	138	

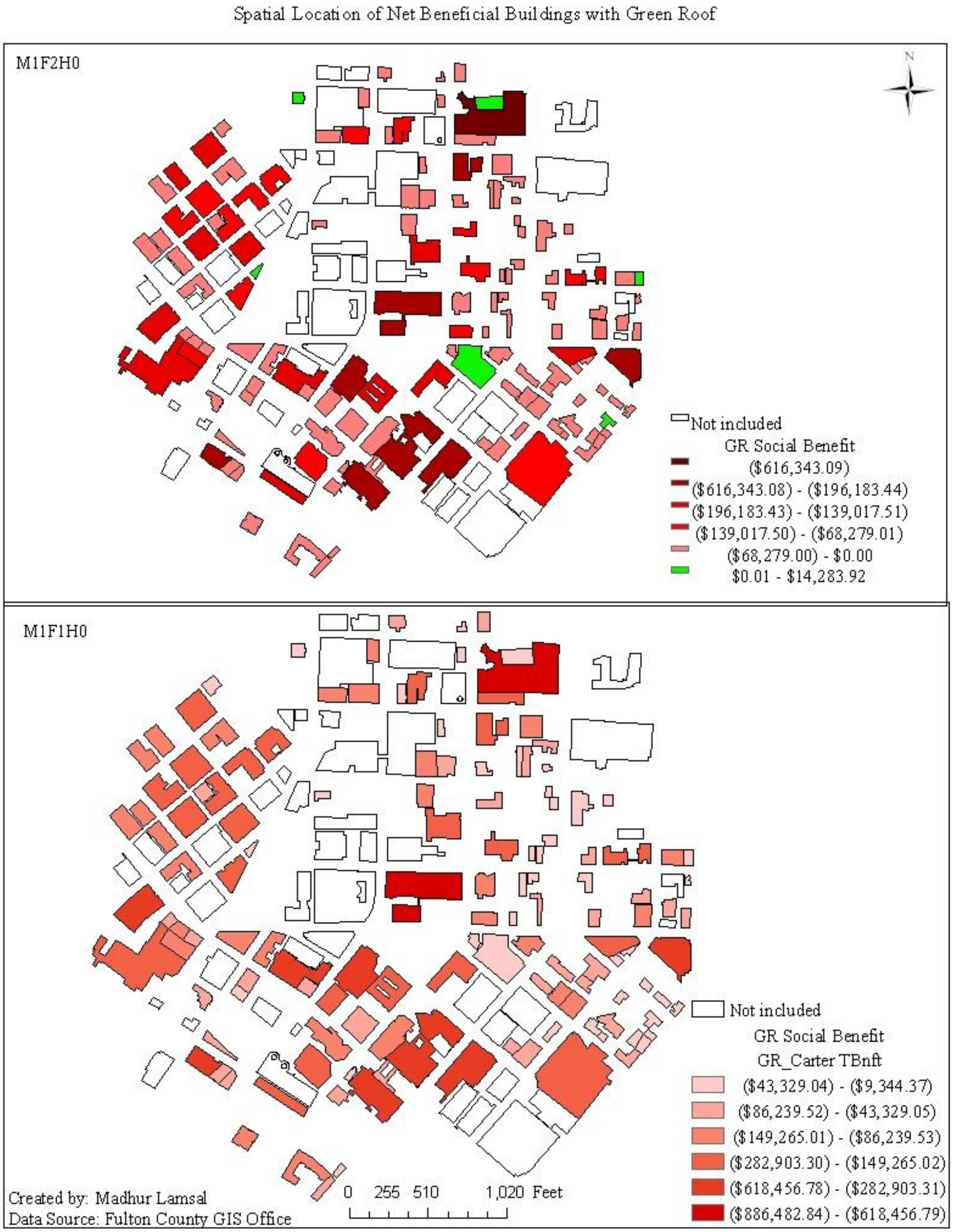


Figure 4.14: Social NPV Building-by-Building under M1F2H0 and M1F1H0

Table 4.15: Social Descriptive Statistics M1F2H0

M1F2H0	GR_S	GR_S per m^2
Mean	-$61,672.49	-36.23
Std. Error	$6,895.44	4.05
Median	-$40,232.98	-23.63
Std. Dev.	$81,003.14	47.58
Minimum	-$616,343.09	-362.04
Maximum	$14,283.92	8.39
Corr. Coef. (roof area v. GR_S and GR_S/m^2)	-0.96	-0.28
Sum	-8,510,802.98	-$4,999.27
Number of Roofs	138	
Beneficial with GR	6	
Not Beneficial with GR	132	

Table 4.16: Social Descriptive Statistics M1F1H0

M1F1H0	GR_S	GR_S per m^2
Mean	-$108,450.59	-$63.70
Std. Error	$10,163.41	$5.97
Median	-$69,559.70	-$40.86
Std. Dev.	$119,393.06	$70.13
Minimum	-$886,482.84	-$520.72
Maximum	-$9,344.37	-$5.49
Corr. Coef. (roof area v. GR_S and GR_S/m^2)	-1.00	-0.51
Sum	- $14,966,181.81	-$8,791.17
Number of Roofs	138	
Beneficial with GR	0	
Not Beneficial with GR	138	

4.3.2 M2F2H0 and M2F1H0 Results

There are 119 buildings that are optimal for green roof adoption from a private perspective out of 138 buildings considered in the study area under M2F2H0 (See Figure 4.15). Under M2F1H0, Privately, the number of optimal green roofs dropped to 15. NPV_{PR} ranges a little over $264,000 to -$ 442,000 over the life of the green roof under F2 and F1 scenario. Table 4.17 and 4.18 presents descriptive statistics for NPV_{PR} associated with M2F2H0 and M2F1H0. Looking at Figure 4.15, there is a spatial dimension for green roof adoption under F2F2H0. However under M2F1H0, optimal green roofs are scattered around spatial with any obvious dimension.

Socially, there are 135 and 133 buildings that are optimal from a social perspective out 138 building considered in the study area (See Figure 4.16) under M2F2H0 and M2F1H0. NPV_S ranges from little more than $568,000 to -$45119 over the life of the green. Table 4.19 and 4.20 presents descriptive statistics NPV_S. Looking at Figure 4.16, it is obvious to argue that green roofs are optimal for the study area.

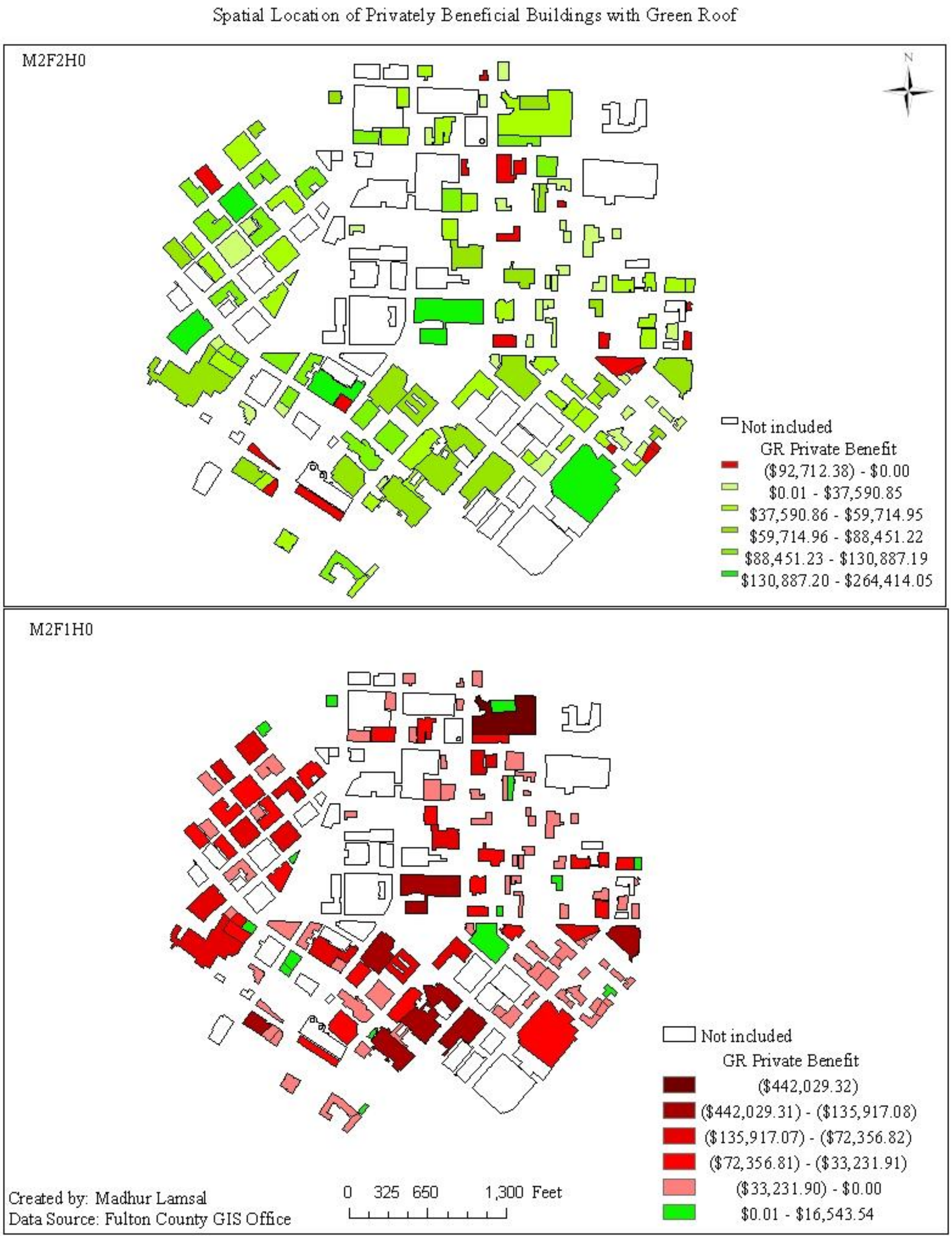


Figure 4.15: Private NPV Building-by-Building under M2F2H0 and M F1H0

Table 4.17: Private Descriptive Statistics M2F2H0

M2F2H0	GR_{PR}	GR_{PR} per m^2
Mean	$48,874.78	38.40
Standard Error	$4,054.72	2.97
Median	$45,790.76	41.02
Std. Dev.	$47,632.14	34.88
Minimum	-$92,712.38	-51.20
Maximum	$264,414.05	168.82
Sum	$6,744,719.03	5,299.21
Corr. Coef. (roof area v. GR_{PR} and GR_{PR}/m^2)	0.4471	-0.2773
Number of Roofs	138	
Beneficial with GR	119	
Not Beneficial with GR	19	

Table 4.18: Private Descriptive Statistics M2F1H0

M2F1H0	GR_{PR}	GR_{PR} per m^2
Mean	-$36,495.32	-14.84
Standard Error	$4,827.17	1.12
Median	-$18,343.91	-16.03
Std. Dev.	$56,706.45	13.10
Minimum	-$442,029.32	-51.20
Maximum	$16,543.54	46.77
Sum	-$5,036,354.12	-2,048.37
Corr. Coef. (roof area v. GR_{PR} and GR_{PR}/m^2)	-0.9589	-0.1347
Number of Roofs	138	
Beneficial with GR	15	
Not Beneficial with GR	123	

Spatial Location of Net Beneficial Buildings with Green Roof

Figure 4.16: Social NPV Building-by-Building under M2F2H0 and M2F1H0

Table 4.19: Social Descriptive Statistics M2F2H0

M2F2H0	GR_S	GR_S per m^2
Mean	$103,443	$60.76
Std. Error	$7,435	$4.37
Median	$86,336	$50.71
Std. Dev.	$87,337	$51.30
Minimum	-$34,423	-$20.22
Maximum	$568,036	$333.67
Sum	$14,275,168	$8,385.27
Corr. Coef. (roof area v. GR_S and GR_S/m^2)	0.87	-0.28
Number of Roofs	138	
Beneficial with GR	135	
Not Beneficial with GR	3	

Table 4.20: Social Descriptive Statistics M2F1H0

M2F1H0	GR_S	GR_S per m^2
Mean	$17,903.73	$10.52
Std. Error	$1,362.68	$0.80
Median	$12,874.36	$7.56
Std. Dev.	$16,007.88	$9.40
Minimum	-$45,119.31	-$26.50
Maximum	$77,342.89	$45.43
Sum	$2,470,714.94	$1,451.30
Corr. Coef. (roof area v. GR_S and GR_S/m^2)	0.03	-0.14
Number of Roofs	138	
Beneficial with GR	133	
Not Beneficial with GR	5	

4.3.3 M3F2H0 and M3F1H0 Results

There are not any buildings that are optimal for green roof adoption from a private perspective out of 138 buildings considered in the study area under M3F2H0 (See Figure 4.17) under M3F1H0 and M3F1H0. NPV_{PR} generates loss little over 623,000-$719,000 over the life of the green roof under F2 and F1 scenario. Table 4.21 and 4.22 presents descriptive statistics for NPV_{PR} associated with M3F2H0 and M3F1H0. Looking at Figure 4.17, it is clear that green roofs are no optimal roofing scenario if energy benefit is limited to F2 and F1 scenario under M3.

Socially, there are 4 and 0 buildings that are optimal from a social perspective out 138 building considered in the study area (See Figure 4.18) under M3F2H0 and M3F1H0. NPV_S ranges from $4,888 to -$324,000 over the life of the green roof. Table 4.23 and 4.24 presents descriptive statistics NPV_S. Looking at Figure 4.18, it is obvious to argue that green roofs are not optimal for the study area under M3F1 and M3F2.

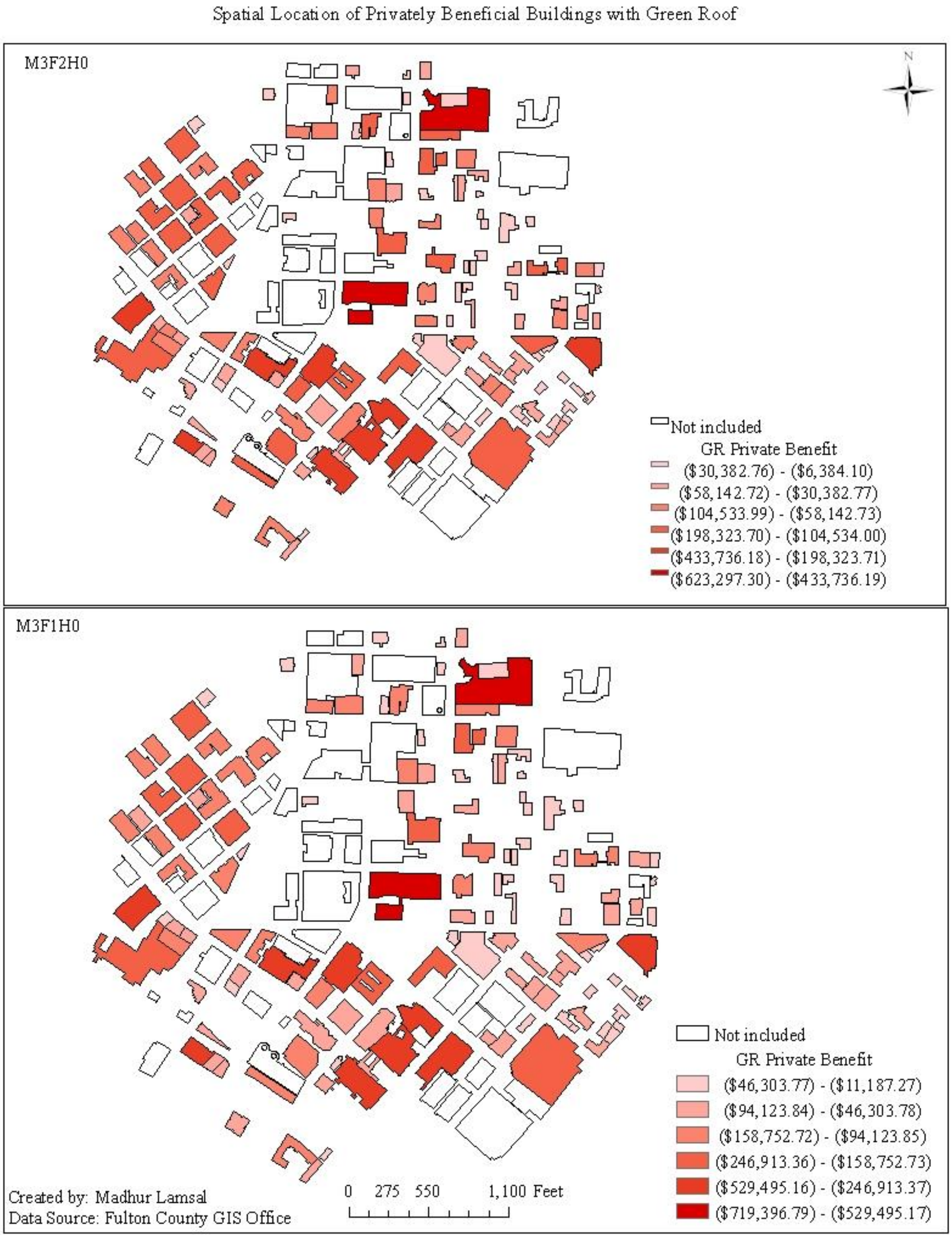


Figure 4.17: Private NPV Building-by-Building under M3F2H0 and M3F1H0

Table 4.21: Private Descriptive Statistics M3F1H0

M3F2H0	GR_{PR}	GR_{PR} per m^2
Mean	-$77,311.89	-$43.52
Standard Error	$7,143.07	$0.58
Median	-$50,727.46	-$43.01
Std. Dev.	$83,912.08	$6.81
Minimum	-$623,297.30	-$61.02
Maximum	-$6,384.10	-$18.05
Sum	-$10,669,041.32	-$6,005.79
Corr. Coef. (roof area v. GR_{PR} and GR_{PR}/m^2)	-0.9951	-0.2773
Number of Roofs	138	
Beneficial with GR	0	
Not Beneficial with GR	138	

Table 4.22: Private Descriptive Statistics M3F1H0

M3F1H0	GR_{PR}	GR_{PR} per m^2
Mean	-$93,986	-$53.92
Standard Error	$8,370	$0.22
Median	-$61,624	-$54.15
Std. Dev.	$98,328	$2.56
Minimum	-$719,397	-$61.02
Maximum	-$11,187	-$41.89
Sum	-$12,970,032	-$7,440.86
Corr. Coef. (roof area v. GR_{PR} and GR_{PR}/m^2)	-0.9995	-0.5024
Number of Roofs	138	
Beneficial with GR	0	
Not Beneficial with GR	138	

Spatial Location of Net Beneficial Buildings with Green Roof

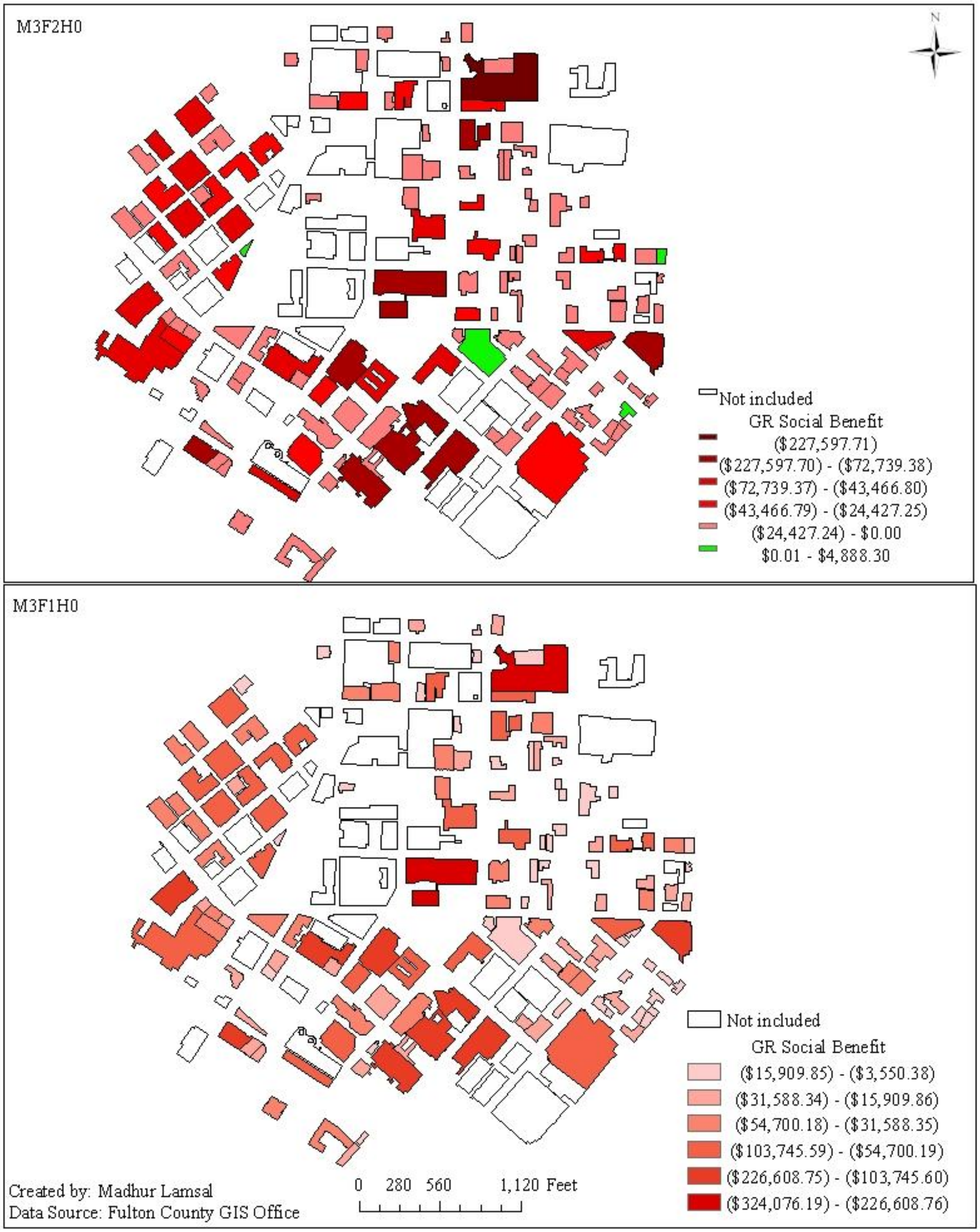


Figure 4.18: Social NPV Building-by-Building under M2F2H0 and M2F1H0

Table 4.23: Social Descriptive Statistics M3F2H0

M3F2H0	GR_S	GR_S per m^2
Mean	-$23,051.50	-$13.54
Std. Error	$2,547.19	$1.50
Median	-$15,037.25	-$8.83
Std. Dev.	$29,922.74	$17.58
Minimum	-$227,597.71	-$133.69
Maximum	$4,888.30	$2.87
Sum	-$3,181,106.97	-$1,868.59
Corr. Coef. (roof area v. GR_S and GR_S/m^2)	-0.96	-0.28
Number of Roofs	138	
Beneficial with GR	4	
Not Beneficial with GR	134	

Table 4.24: Social Descriptive Statistics M3F1H0

M3F1H0	GR_S	GR_S per m^2
Mean	-$39,757.97	-$23.35
Std. Error	$3,717.67	$2.18
Median	-$25,573.20	-$15.02
Std. Dev.	$43,672.72	$25.65
Minimum	-$324,076.19	-$190.36
Maximum	-$3,550.38	-$2.09
Sum	-$5,486,599.41	-$3,222.84
Corr. Coef. (roof area v. GR_S and GR_S/m^2)	-$1.00	-$0.51
Number of Roofs	138	
Beneficial with GR	0	
Not Beneficial with GR	138	

Across the three methods, M2 leads to the highest number of buildings for which a green roof is the optimal type under. This is true when looking at both NPV_{PR} and NPV_S. However, under F1, the optimal number of green roofs dropped to 15. One reason is that M2 assume 51%

of energy saving per floor, which is the highest benefit scenario across the three methods. One floor energy saving scenario (F1) does not have single optimal green roof type that are neither privately nor socially optimal for M1 and M3 respectively. However, socially M1 and M3 have only 6 and 4 optimal green roofs under F2 respectively.

4.4 Comparative Analysis of Scenario

It is found that M2 outperforms other two methods in each scenario presented above. It is evident in all NPV_{PR} and NPV_{S}. There are two primary reasons that turns M2 favorable compared to M1 and M3. One, M2 has 51% of energy saving scenario whereas M1 and M3 have 28% and 10%. The other reason, the difference of installation cost of conventional and green roof is $ 65 for M2 whereas M1 and M3 have $71.63 and $67. The energy saving percent and the difference in installation costs are the major cost drivers that can influence overall cost-benefit of the project. The factor that contributes a little is health care benefit associated avoided green house gas from coal-fired power plants due to reduced kilowatt demand with green roofing scenario. The benefit does not exceed more than $77,000 even high estimation scenario of M2F4H0. The following two tables depict the number of buildings that are privately and socially optimal for green roofs.

Table 4.25 Number of Privately Beneficial Green Roofs

Floors	M1	M2	M3
4	42	119	7
3	14	119	1
2	1	119	0
1	0	14	0

Table 4.26 Number of Socially Beneficial Green Roof

Floors	M1	M2	M3
4	63	135	73
3	52	135	50
2	6	135	4
1	0	133	0

The forty year detailed cost-benefit estimates for all the methods are presented at the end of the chapters.

4.5 Economic Analysis of Green Roof Adoption and Positive Externality

4.5.1 Energy Benefit under UHIE Reduction

A scenario of 1-6 ^{0}F UHIE reduction is examined to capture the scope of additional benefit for 100 % green roofing on all 138 buildings. The following figure suggests that if green roof can reduce localized UHI from 1-6 ^{0}F, there is a scope for additional benefits that ranges from $4-$24 million over forty year period.

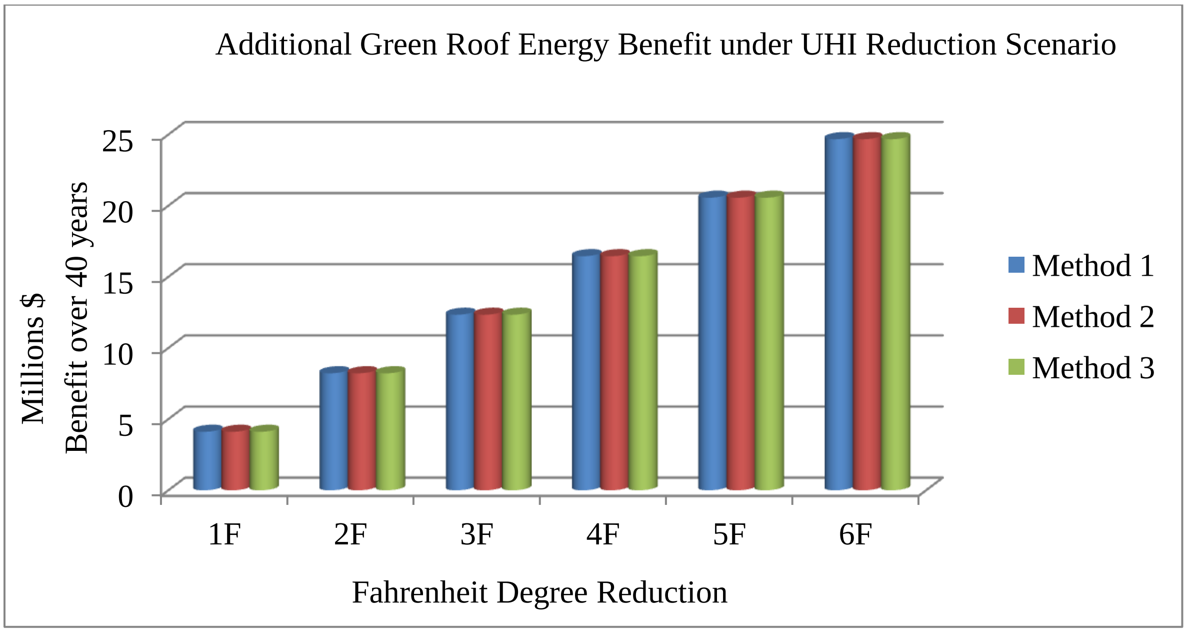
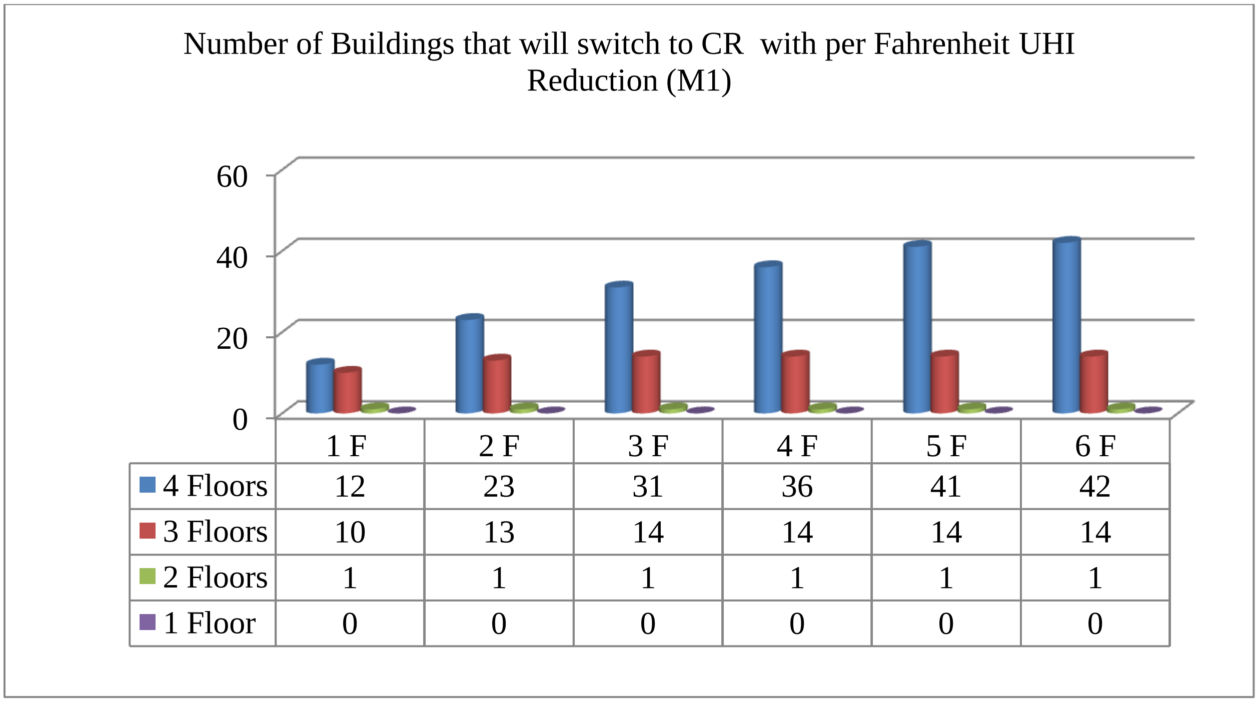


Figure 4.19: Energy Benefit under UHI Reduction

4.5.2 UHIE Reduction, Externality & Freerider

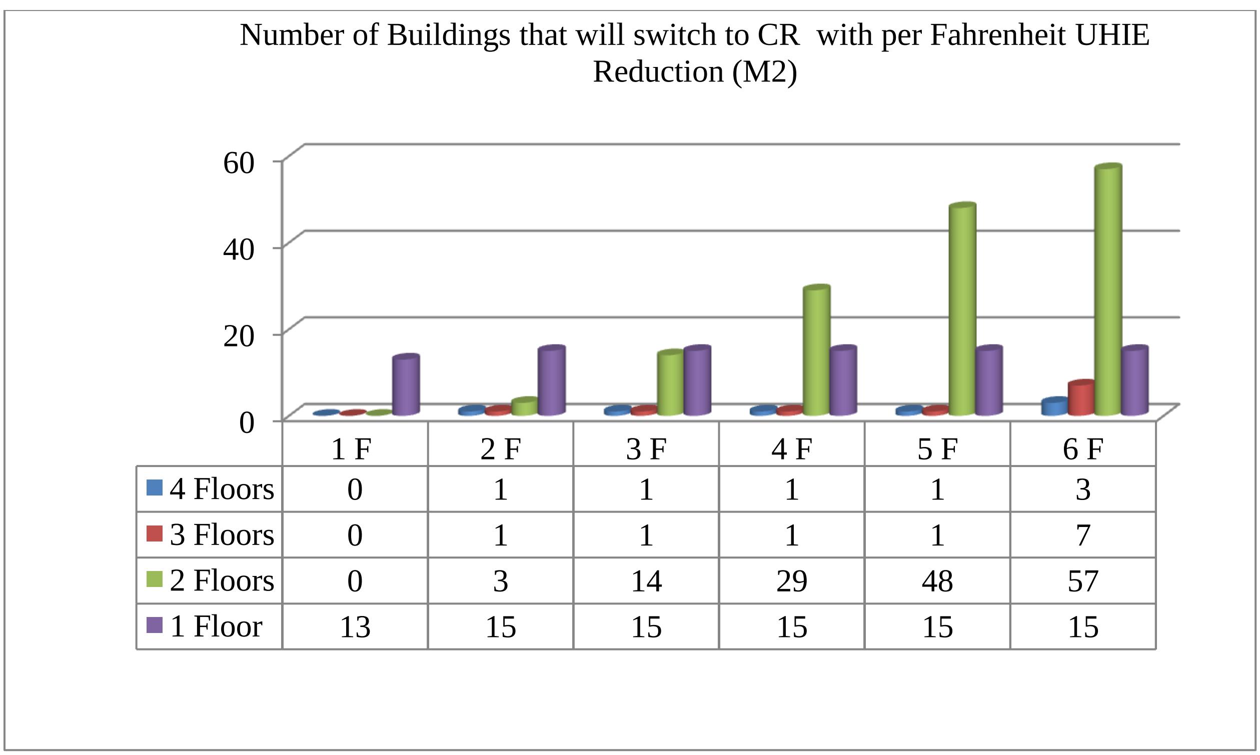
Under the 1-6 ^{0}F UHIE reduction scenarios, the buildings that will switch from green roof to conventional roof to enjoy the cost free rider benefits are explored. Figures 4.20 to 4.22 reveal that a private green roof adoption decision is independent of accounting prevalent ambient air-cooling effect due to surrounding green roofs if energy saving with the green roof is limited to one or two floors below the green roof. Under low energy saving scenario of 28 and 10 percent per floor for M1and M3 respectively, the reduction in the UHI does not encourage a green roof adopter to switch to conventional roof to enjoy the cost free benefit, if energy saving with the green roof is being realized up to 4 or 3 floors below the green roof. Under M2, there are very few buildings that can switch to conventional roof even under the 6 ^{0}F UHI reduction if energy saving is realized up to 4 or 3 floors below the green roof.

The analysis suggest that the UHI reduction alone may not encourage a green roof adopter to switch to the conventional roof if private energy benefits with the green roofs is realized up to more than two floors below the green roofs. However, under the 2 or 1 floors energy saving below the green roofs, as the UHIE decrease, the phenomenon of switching to conventional roof can increase with each UHI Fahrenheit decrease.   The following figure (4.20,4.21, and 4.22) present the number of green roofs that can switch to convectional roof under per 0F UHI reduction privately for M1, M2, and M3 respectively.



	1 F	2 F	3 F	4 F	5 F	6 F
4 Floors	12	23	31	36	41	42
3 Floors	10	13	14	14	14	14
2 Floors	1	1	1	1	1	1
1 Floor	0	0	0	0	0	0

Figure 4.20: Ambient Air Cooling Effect and Freeriders under M1



	1 F	2 F	3 F	4 F	5 F	6 F
4 Floors	0	1	1	1	1	3
3 Floors	0	1	1	1	1	7
2 Floors	0	3	14	29	48	57
1 Floor	13	15	15	15	15	15

Figure 4.21: Ambient Air Cooling Effect and Freeriders under M2

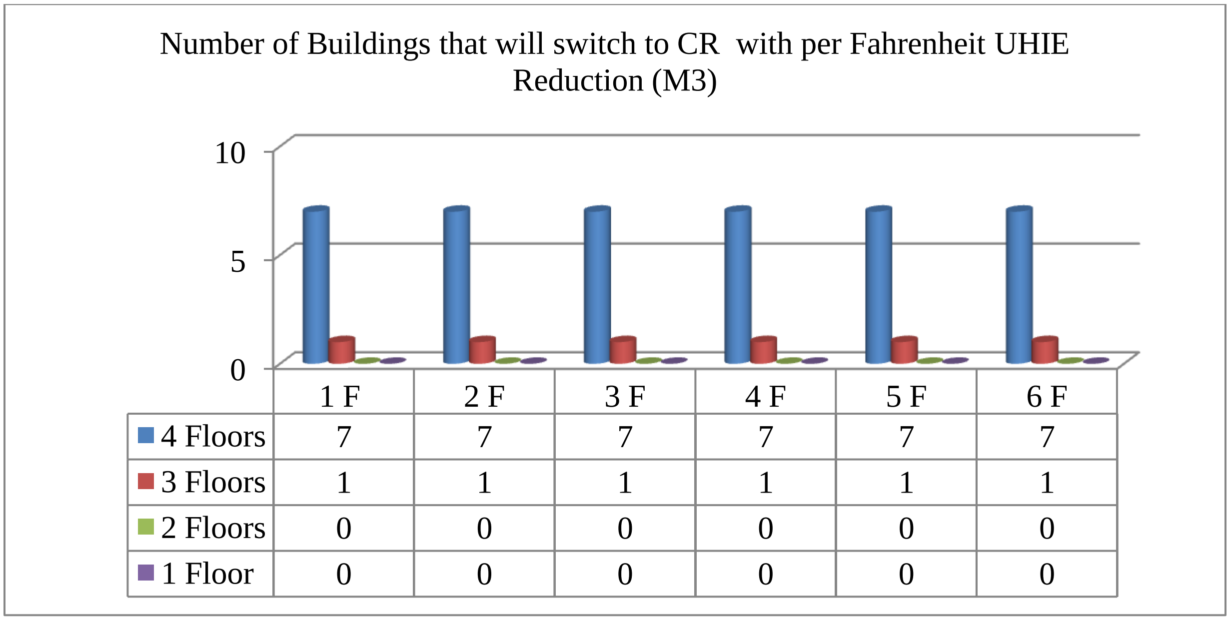
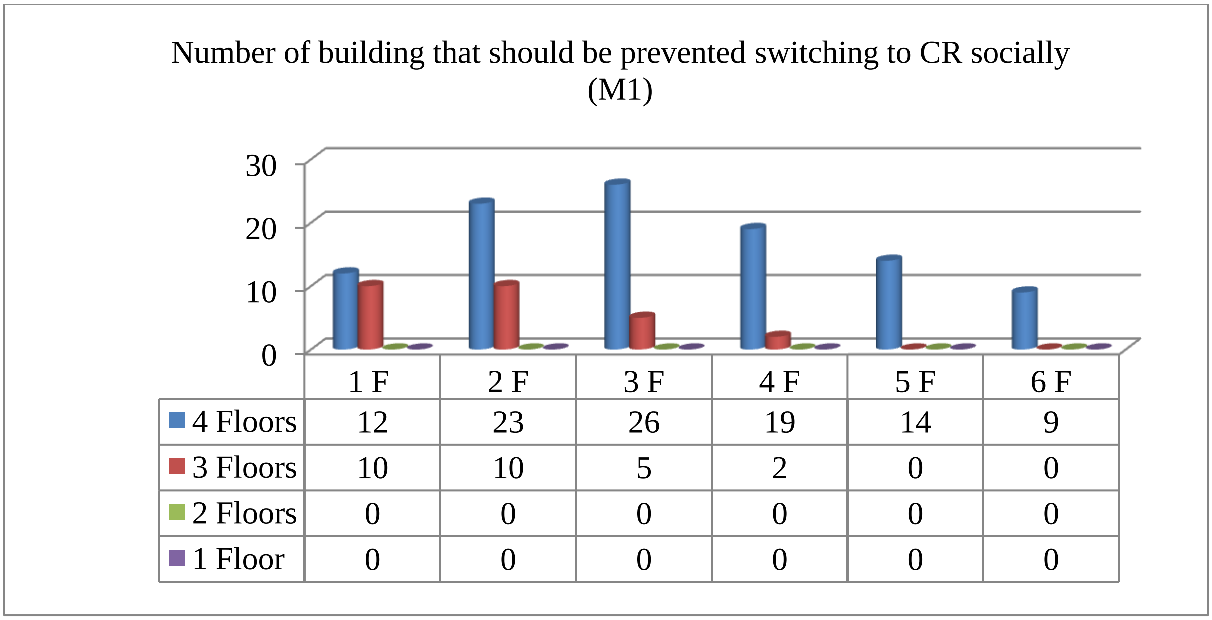


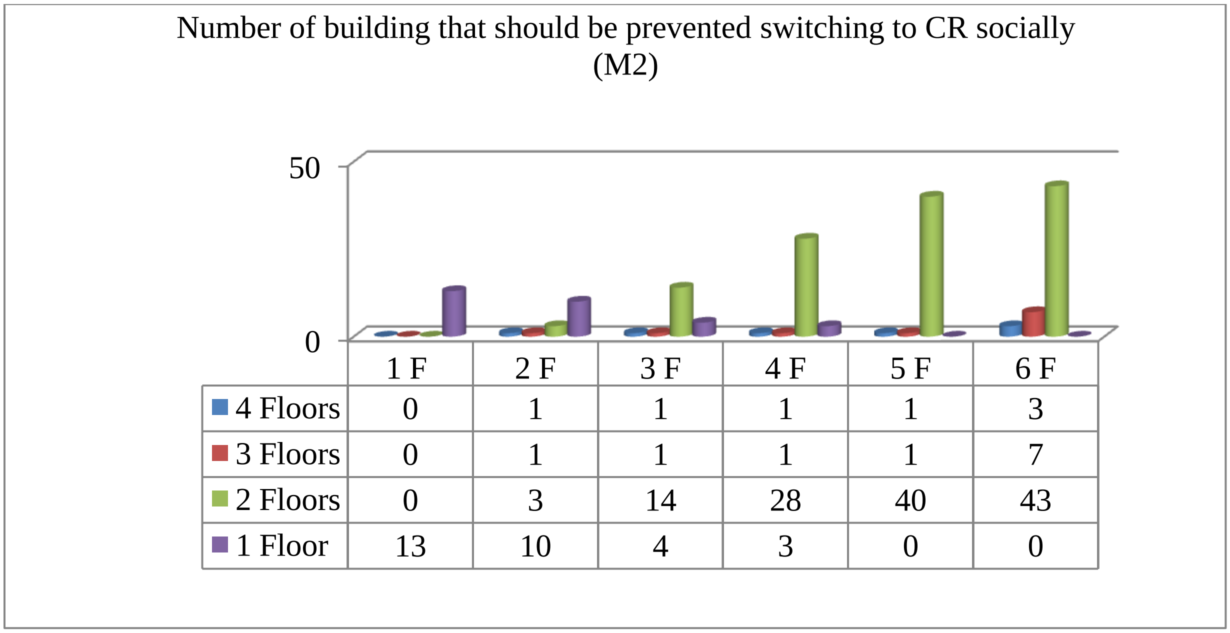
Figure 4.22: Ambient Air Cooling Effect and Freeriders under M3

It is also examined that, under 1-6 ^{0}F UHI reduction, how many buildings should be prevented from switching to conventional roof from green roof socially. The following are the figures (4.23, 4.24, and 4.25) for the analysis. Figures 4.23 and 4.24 suggest that if energy benefit of a green roof can be realized up to 2 or 1 floor below the green roof, then, under the 1-6 ^{0}F degree UHIE reduction, a green roof adopter would not consider available benefit available due to reduced UHIE before adoption decision under methods 1 and 3. Therefore, socially there are not many rooftops that will switch to conventional roof from green roof. However, figure 4.24 reveals that for 4 or 3 floors energy saving scenario, the net private energy benefit is much higher than the scope for private benefit due to UHIE reduction. Therefore, socially there are fewer buildings that can switch to conventional roof from green roofs under UHIE reduction of 1-6 ^{0}F in method 2. However, if energy benefit is limited to 2 or 1 floor below the green roof, maximum of 43 building can switch to the conventional roof under 6 ^{0}F UHI reductions in method 2. The analysis suggest that if the green roof energy benefit per floor is higher and such benefits are realized up to as many as four floors below the green roofs, then socially, fewer (0-26) buildings should be prevented from switching to conventional from green roofs.



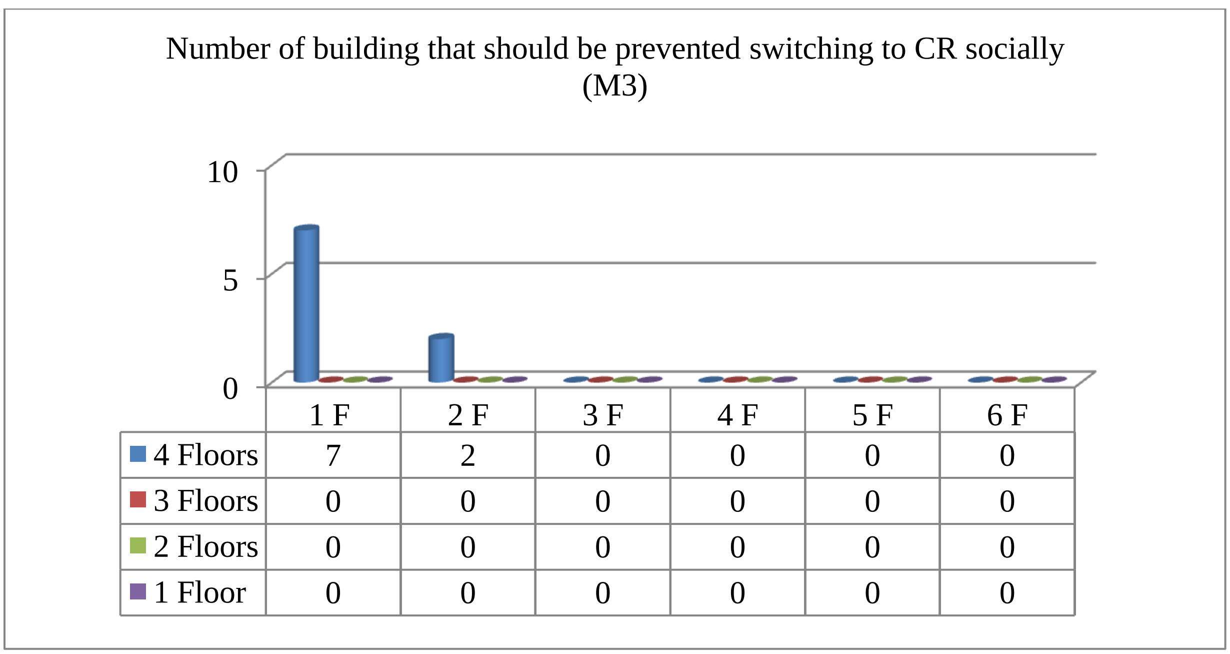
	1 F	2 F	3 F	4 F	5 F	6 F
4 Floors	12	23	26	19	14	9
3 Floors	10	10	5	2	0	0
2 Floors	0	0	0	0	0	0
1 Floor	0	0	0	0	0	0

Figure 4.23: Ambient Air Cooling Effect and Socially Beneficial Buildings under M1



	1 F	2 F	3 F	4 F	5 F	6 F
4 Floors	0	1	1	1	1	3
3 Floors	0	1	1	1	1	7
2 Floors	0	3	14	28	40	43
1 Floor	13	10	4	3	0	0

Figure 4.24: Ambient Air Cooling Effect and Socially Beneficial Buildings under Method 2



	1 F	2 F	3 F	4 F	5 F	6 F
4 Floors	7	2	0	0	0	0
3 Floors	0	0	0	0	0	0
2 Floors	0	0	0	0	0	0
1 Floor	0	0	0	0	0	0

Figure 4.25: Ambient Air Cooling Effect and Socially Beneficial Buildings under Method 3

4.5.3 Cooling Effect Buffer & Energy Saving Percent

The following (figure 4.26) was produced in Arc GIS using equation 3.4 exponential decay function. The blue bands around the each rooftop represent the ambient air-cooling effect of each green roof. The magnitude of such band is highly uncertain and depends on lambda (λ); the decay constant is used in the exponential decay function. The numbers in each shape polygon represents the energy benefit percentage of net private benefit generated by each green roof. The number presented in Fig. 4.26 is for scenario M2F4. This number will vary according to scenario examined. If any building can capture energy saving percent benefit due to the cooling effect of next-door green roof, it can be assumed that such a green roof would switch back to conventional roof to enjoy cost free ride.

Figure 4.26 shows analysis result done for M2F4. The map suggests that smaller green roof area may not produce bigger buffer area of cooling effect. Therefore, may not be able to influence its neighbor's energy demand noticeably. However, bigger roof size as in four roofs in figure 4.26 can influence neighboring smaller roof size buildings' energy demand if the neighboring buildings are of the same height. For all the GIS analysis, building specific dimensional geometry was excluded. Therefore, role of building height remains unanswered. However, the map suggests that, where smaller roofs are next to a bigger roof, there is a high probability of greater cooling effect that can influence energy cost of smaller roofs.

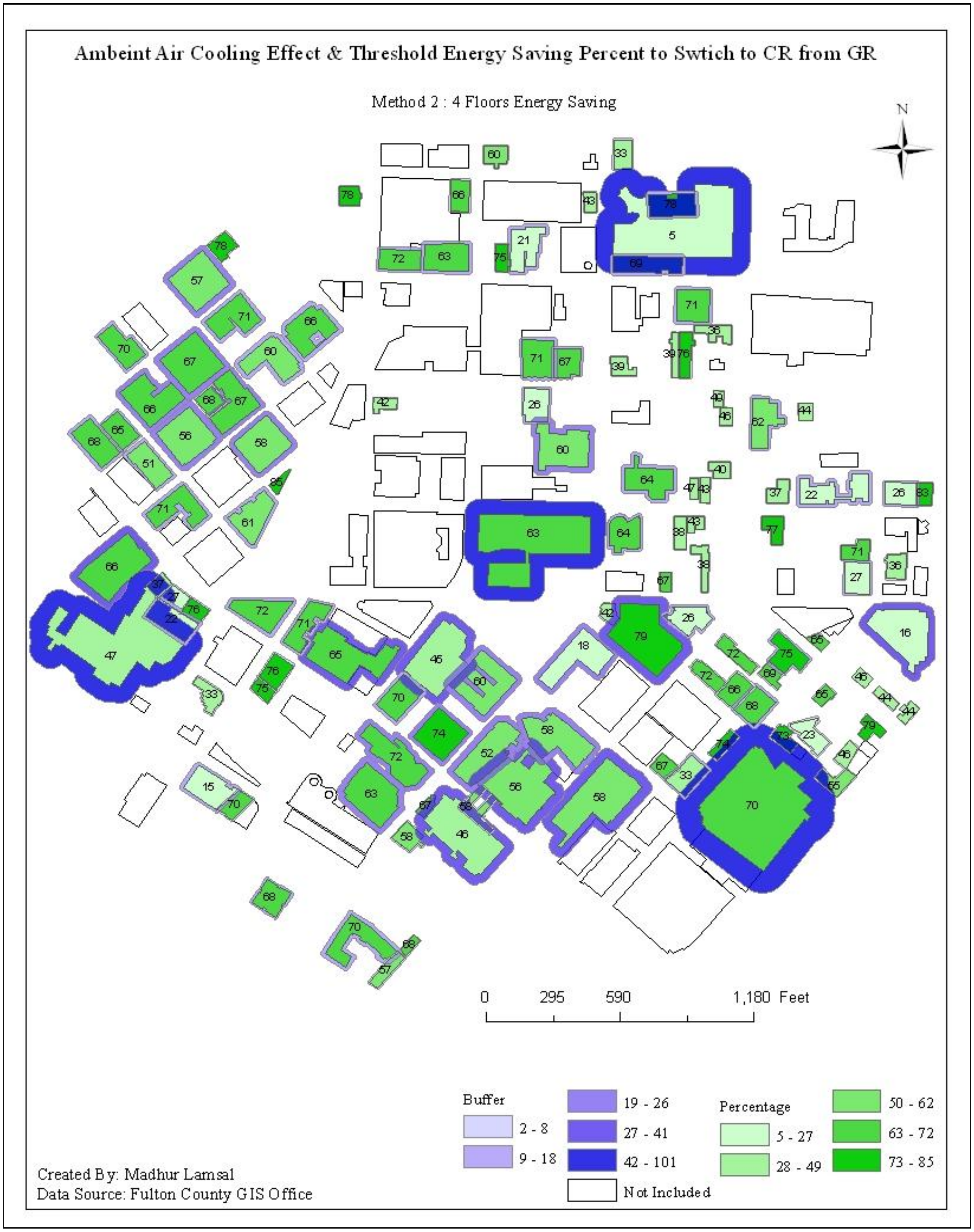
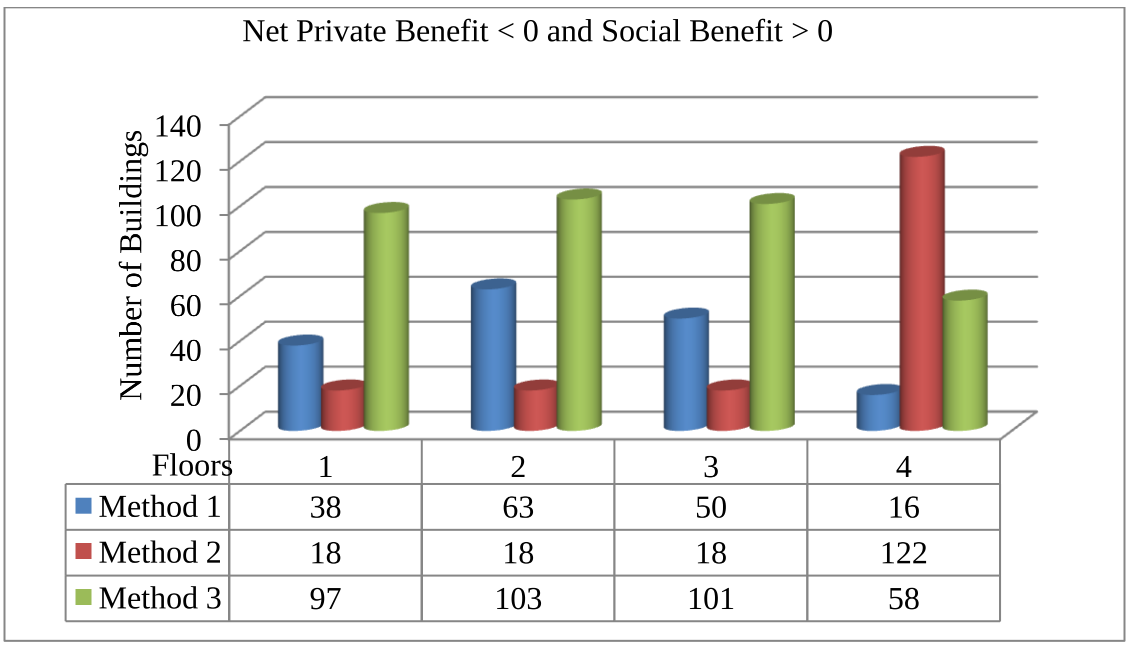


Figure 4.26: Ambient Air Cooling Effect and Threshold Energy Saving Percent

4.5 Subsidy Analysis

Three criteria for the subsidy analysis are tested. Tested criteria are explained in section 3.13. The first criteria has 16-63, 18-122, 58-103 (figure 4.27) roofs that are found to be ideal candidate to approach for green roofing systems with a subsidy for method 1, 2, and 3 respectively. Socially, on average, there are 11 to 88 percent of buildings that can benefit society at large with green roofs under F4 to F1 energy saving and M1, M2, and M3 scenario. If these buildings are offered subsidy or tax credit for adopting green roofs, the society can mitigate consequences of urbanization to some extent.



Floors	1	2	3	4
Method 1	38	63	50	16
Method 2	18	18	18	122
Method 3	97	103	101	58

Figure 4.27: Subsidy Analysis (First Criteria)

The results for second criteria are already discussed in section 4.1-4.4.

Third criteria results reveal that there are 1, 20, and 31 buildings that have higher social benefits than the cost difference of installation and maintenance of conventional and green roof under method 1, 2, and 3 respectively. The cost difference of installation rate of conventional and

Green roofs are $71.63, $65, and $67 for method 1, 2, and 3 respectively. The disparity between installation costs contributed that socially, method 3 has the highest number of beneficial buildings even if maintenance costs are included in the study. Figures (4.28-4.36) show the exact location of the buildings that are ideal candidate for the subsidy under three criterias examined.

4.5.1 Cost of Subsidy

An additional analysis was performed to screen that how many buildings out of private and social optimal green roofs type would produce higher benefit than the proxy incentive rate ($53.82/m^2). The results of social and private scenarios are presented below for all three methods and four to one floor energy saving under no UHI.

4.5.1.1 Social Optimal Buildings and Subsidy Cost-Benefit

The following four tables (4.27-4.30) present the number of buildings that generate higher societal benefit than the cost of incentives ($53.82). Table 4.27 has as low as 32% fewer building than the table 4.26, which were found to be socially optimal and beneficial for green roof. For example under M1F4H0; there were 63 building that were found to be optimal and beneficial for green roofs (See Table 4.26). Out of which, 45 roofs are found producing lower societal benefit than the proxy incentive rate. Therefore, such buildings may not produce social surplus as worth of given incentive. These 45 buildings are not the best candidate for incentive reimbursement program as of Portland, Oregon. However, at this time, this section of analysis does not consider UHI mitigation benefits of green roof. Therefore, if UHI mitigation incorporated in the study, the analysis can depicts different picture. The upper bound of net benefit ranges $2,728- almost $20 million and lower bound of benefit ranges $0-$13,629. The following tables details cost-benefit for buildings that have higher societal than the incentive they can receive.

Table 4.27 Number of Green Roof with Social Benefit > $53.82

Floors	M1	M2	M3
4	18	112	1
3	4	112	0
2	0	99	0
1	0	2	0

Table 4.28 Incentive Cost for City

Floors	M1	M2	M3
4	$768,598	$9,944,769	$19,038
3	$117,729	$9,944,769	$0
2	$0	$7,110,377	$0
1	$0	$39,042	$0

Table 4.29 Net Social Benefit for

Floors	M1	M2	M3
4	$417,312.78	$19,733,201.28	$2,728.12
3	$32,496.36	$11,953,692.78	$0
2	$0	$3,224,462.38	$0
1	$0	$13,629.83	$0

Table 4.30 Net Benefit per Meter Square after Incentive

Floors	M1	M2	M3
4	$29.22	$106.79	$7.71
3	$2.28	$64.69	$0
2	$0	$17.45	$0
1	$0	$0.07	$0

4.5.1.2 Private Optimal Building and Subsidy Cost-Benefit

The following four tables (4.30-4.34) present the number of buildings that generate higher private benefit than the incentives they can receive. The upper bound of net benefit ranges $0- almost $9 million and lower bound of benefit zero.

Table 4.31 Number of green roof private benefit > $53.82

Floors	M1	M2	M3
4	8	94	0
3	2	93	0
2	0	44	0
1	0	0	0

Table 4.32 Cost of incentive for city

Floors	M1	M2	M3
4	$281,670	$8,981,434	$0
3	$39,042	$8,797,419	$0
2	$0	$1,897,443	$0
1	$0	$0	$0

Table 4.33 Net Private Benefit minus incentive

Floors	M1	M2	M3
4	$100,020.53	$14,127,722.05	$0
3	$8,234.62	$6,360,984.52	$0
2	$0	$566,006.62	$0
1	$0	$0	$0

Table 4.34 per meter square private benefit minus incentive

Floors	M1	M2	M3
4	$19.11	$84.66	$0
3	$1.57	$38.12	$0
2	$0	$3.39	$0
1	$0	$0	$0

NOTE: SEE PAGE THROUGH (129-140) FOR DETAILIED SUMMARY OF CALCULATION AND (141-157) FOR GIS ANALYSIS MAPS.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study reveals a number of important factors for both private and public sector to consider green roofs as a viable option to mitigate consequences of urbanization. Green roof has double life span than conventional roof (Clark, et.al, 2008), which already gives 100% benefit at the time of installation. Such an opportunity should have been one good reason for the success of green roof technology; however it is still not very popular in North America. Green roof can also help to reduce other costs borne due to increased impervious surfaces in and around the city such as higher energy demand, stormwater management, moderate UHI effect and health care cost.

The building-by-building NPV analysis reveals that under NPV_{PR} if energy benefit with a green roof is realized as many as four floors below the green roof then there would be spatial dimension for optimal roof type; green roof especially under method two and method one. However, such a spatial dimension of optimal green roof type under NPV_{PR} decreases quickly as the energy saving scenario below the green roof changes from 4,3,2, to 1 floor especially under method one and three. Method two is found to have highest number of privately optimal green roof type under the three scenarios examined. This is due to the fact that method two assumes fifty one percent of energy saving per floor with green roof and difference between installations cost of conventional and green roof type is the lowest $65 under method 2. Other two methods, energy saving parameters is limited to 28% and 10% per floor, where as cost difference of installation cost of conventional and green roof type is $71.63 and $67 for method one and three respectively.

The building-by-building social benefit (NPV_S) analysis suggests that there is a spatial dimension for optimal green roof type if energy benefit realized up to the four or three floors below the green roofs. Again, method two outperforms method one and three. If energy benefit is limited to two or one floor below the green roof, method one and two do not produce any spatial dimension of optimal green roof type.

The private and social benefits of green roof depend on roof size, location, orientation, building characteristic, and building activity. This study reveals that privately there are 0 to 119 buildings that can benefit from green roofs depending upon energy saving scenario. Privately, it is plausible to argue that in presence of five times higher maintenance cost, a green roof can be cost-effective. However, under net social benefit, up to 136 building are found be optimal for green roof type suggesting that green roofs can be promoted as a mitigation tool to confront consequences of urbanization.

If UHI mitigation (1-6 ^{0}F) is included in the study, it can alone produce additional $4-$24 millions for 100 % green roofing of the study area. The UHI reduction can be categorized as positive externality of green roofs. For any action that has positive externality, there is always scope for free riders. This study reveals that if the green roofs' net private energy benefit is limited to only one or two floors below the green roofs, then there is a high chance that a green roof adopter will switch back to conventional roof to enjoy cost free ride if UHI reduction (1-6 ^{0}F) exists with 100% green roofing scenarios. The buffer and hot spot analysis revealed that larger green roofs have greater social benefits and can cool ambient air around it to some extent.

However, ambient air cooling effect of a green roof is highly uncertain to influence next-door neighbor green roof adoption decision. It is found that any building with greater area of flat roof surface would be capable of producing greater social benefits.

The subsidy analysis suggests that under the three criterions tested, there are as many as 1-88% of building that can benefit the society with the green roofs. A flat incentive to all new green roof installation can be assigned such as $5 (53.82/m^2) per square feet of Portland, Oregon (Portland Bureau of Environmental Services 2012). Such program lasts until the fund gets exhausted. However, an additional analysis performed, suggests that all socially and privately optimal new green roof installation may not produce higher societal benefit than the $5 ($53.82) incentive rate.

Privately, So far, inside the Atlanta region, reduction in energy consumption is the only private benefit that can be realized with the green roofs. In aggregate, the upper bound of private energy benefit can alone be twenty two millions dollar over 40-year period for 100% greening scenario of study area. In the near future, if stormwater fee is implemented, a green roof owner will pay reduced fee or no fee. For example, city of Ann Arbor, Michigan considers green roof as pervious surface, therefore green roof owners pay $0 per year (Clark, et.al, 2008). It can be hypothesized that any stormwater fee ordinance for Atlanta, in future, will consider green roof as a viable candidates for water quality credit or reduced stormwater fee. The neighboring county of Atlanta, City of Gwinnet, GA gives 10% of water quality credit to green roof owners (Department of Water Resources Gwinnet County, GA 2011). The parameter estimates used in this analysis suggest that $1, and $1.8 million private and public (stormwater infrastructure) costs can be saved if green roofs are adopted on all 138 buildings in the study area.

The societal benefits associated with green roof adoption are realized through reduction in energy demand as well as reduction in urban heat island, lower cost for stormwater management, improved ambient air quality, lower health care costs, and reduced emission of greenhouse gases from coal-fired power plants. Greening 138 buildings of the study area would produce $13 million social benefit over 40 years. Extrapolating this benefit to city scale greening would produce much greater benefit, which is not conducted at this time. However, a study has calculated the 100% greening roof tops of city of Toronto, Canada would produce $37 million annual social benefit (Banting, et al., 2005). Another study found that 50% greening scenario would produce $ 12 million annual social benefit for New York City (Acks, 2006). Analysis of 100% greening scenarios of Detroit and Chicago were also close to the New York and Toronto social benefits (Clark, et.al, 2008). Therefore, it is not implausible to iterate that 100% green roofing of Atlanta roof tops would produce societal benefit in and around by the same range as previous studies.

4.3 Recommendations for Further Research

Most green roof benefit quantification relates to extensive green roof scenarios only, which may not be very suitable for different climatic zones. There is a very thin array of literature that includes benefits of intensive green roof scenarios, though intensive green roofs are suitable for local vegetation. Extensive green roof studies relate to the benefits of sedum plant family members. Additional research is required to address the remaining question: how does benefit scenarios change if local plants are included in the green roof study. A mesoscale climate analysis with actual weather data would be ideal to test the effect of native vegetation on ambient air-cooling effect and improvement of quality. There are not enough studies that pin down a degrading function for ambient air-cooling effect of green roof vegetation.

Economically, the major obstacle to promote green roof technologies lies within the premium cost of installation. The installation cost of green roof is generally 50-85% higher than the conventional roof (Clark, et.al, 2008). Because of the higher societal benefit associated with green roof technology, the local government as well as federal government should incorporate dedicated programs to promote green roof technology. However, non-market good, benefits associated with the green roofs are hard to monitor and govern with a specific economic program. Academics and interest group should focus on formulating efficient structure for green roof promotion, which needs to be explored within the domain of economics and environmental studies.

REFERENCES

Acks, K. 2006. "A Framework for Cost-Benefit Analysis of Green Roofs: Initial Estimates." *Cost Benefit Group LLC*.

Akbari, H., S. Davis, J. Huang, S. Dorsano, and S. Winnett. "Cooling our communities: a guidebook on tree planting and light-colored surfacing." Lawrence Berkeley Lab., CA (United States); Environmental Protection Agency, Washington, DC (United States). Climate Change Div.

Alexandri, E., and P. Jones. 2008. "Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates." *Building and Environment* 43(4):480-493.

Banting, D., H. Doshi, J. Li, P. Missios, A. Au, B.A. Currie, and M. Verrati. 2005. "Report on the environmental benefits and costs of green roof technology for the city of Toronto." *City of Toronto and Ontario Centres of Excellence—Earth and Environmental Technologies, October* 31.

Bergstrom, J.C., and A. Randall. 2010. *Resource Economics: An Economic Approach to Natural Resource and Environmental Policy*: Edward Elgar Pub.

Bluestone, P. 2010. "An Analysis of Water Related Infrastructure Spending in Georgia " *Fiscal Research Center, Andrew Young School of Policy Studies,Georgia State University* November (212).

Blum, L.N., L.B. Bresolin, and M.A. Williams. 1998. "Heat-related illness during extreme weather emergencies." *JAMA: The Journal of the American Medical Association* 279(19):1514.

Booth, D.B. 1991. "Urbanization and the natural drainage system—impacts, solutions, and prognoses." *The Institute for Environmental Studies* 7(1).

Brown, K.S. 1997. "A decent proposal? EPA's new clean air standards." *Environmental health perspectives* 105(4):378.

Brunekreef, B., and S.T. Holgate. 2002. "Air pollution and health." *The Lancet* 360(9341):1233-1242.

Burke, P.M., G. Nelson, and W. Rickerson. 2007. "Boston's green affordable housing program: Challenges and opportunities." *NYUJ Legis. & Pub. Pol'y* 11:1.

Ca, V.T., T. Asaeda, and E.M. Abu. 1998. "Reductions in air conditioning energy caused by a nearby park." *Energy and Buildings* 29(1):83-92.

Carter, T., and A. Keeler. 2008. "Life-cycle cost–benefit analysis of extensive vegetated roof systems." *Journal of Environmental Management* 87(3):350-363.

Center for Disease Control and Prevention, Emergency Preparedness and Response.2012." Extreme Heat: A Prevention Guide to Promote Your Personal Health and Safety". http://www.bt.cdc.gov/disasters/extremeheat/heat_guide.asp.

Clark, C., P. Adriaens, and F.B. Talbot. 2008. "Green roof valuation: A probabilistic economic analysis of environmental benefits." *Environmental science & technology* 42(6):2155-2161.

Cummings, J.B., C.R. Withers, J. Sonne, D. Parker, R.K. Vieira, F.S.E. Center, D. Jackson, D. Norvell, and P. Plant. 2007. "Recommissioning, Green Roofing Technology, and Building Science Training; Final Report. Cocoa, FL: Florida Solar Energy Center.".

Currie, B.A., and B. Bass. 2008. "Estimates of air pollution mitigation with green plants and green roofs using the UFORE model." *Urban Ecosystems* 11(4):409-422.

Department of Water Resources Gwinnet County, GA. Stormwater Credit Manual. 2011. http://www.gwinnettcounty.com/static/departments/publicutilities/pdf/2011CreditsManual.pdf.

Dimoudi, A., and M. Nikolopoulou. 2003. "Vegetation in the urban environment: microclimatic analysis and benefits." *Energy and Buildings* 35(1):69-76.

Dixon, P.G., and T.L. Mote. 2010. "Patterns and causes of Atlanta's urban heat island–initiated precipitation."

Dousset, B., and F. Gourmelon. 2003. "Satellite multi-sensor data analysis of urban surface temperatures and landcover." *ISPRS Journal of Photogrammetry and Remote Sensing* 58(1-2):43-54.

Dunnett, N., and N. Kingsbury. 2008. *Planting green roofs and living walls*: Timber Press.

Field, B.C. 1994. *Environmental economics: an introduction*: McGraw-Hill Book Company (UK) Ltd.

Geoghegan, J., L.A. Wainger, and N.E. Bockstael. 1997. "Spatial landscape indices in a hedonic framework: an ecological economics analysis using GIS." *Ecological economics* 23(3):251-264.

Georgia Power. 2011. "Facts & Figures." http://www.georgiapower.com/about/facts.asp.

Georgia Secretary of State.2012. Georgia Water Quality Control Act. http://rules.sos.state.ga.us/docs/391/3/6/16.pdf.

Georgia Secretary of State. 2012. Georgia Water Quality Control Act. http://rules.sos.state.ga.us/pages/GEORGIA_DEPARTMENT_OF_NATURAL_RESOURCES/ENVIRONMENTAL_PROTECTION/WATER_QUALITY_CONTROL/index.html.

Getter, K.L., D.B. Rowe, and J.A. Andresen. 2007. "Quantifying the effect of slope on extensive green roof stormwater retention." *Ecological Engineering* 31(4):225-231.

Goodstein, E.S. 2010. *Economics and the Environment*: Wiley.

Green Roof for Healthy Cities. 2012. " Green Roof Benefits." http://www.greenroofs.org/index.php/about-green-roofs/green-roof-benefits.

Grimmond, C., and T. Oke. 2010. "Heat storage in urban areas: Local-scale observations and evaluation of a simple model."

Grimmond, C., and T.R. Oke. 2002. "Turbulent heat fluxes in urban areas: Observations and a local-scale urban meteorological parameterization scheme (LUMPS)." *Journal of Applied Meteorology* 41(7):792-810.

Gwinnet County, Department of Water Resources.2011. Stormwater Credit Manuals. http://www.gwinnettcounty.com/static/departments/publicutilities/pdf/2011CreditsManual.pdf

Hathaway, A., W. Hunt, and G. Jennings. 2008. "A field study of green roof hydrologic and water quality performance." *Transactions of the ASABE* 51(1):37-44.

Heiple, S., and D.J. Sailor. 2008. "Using building energy simulation and geospatial modeling techniques to determine high resolution building sector energy consumption profiles." *Energy and Buildings* 40(8):1426-1436.

Hoag, D.L., and J.S. Hughes-Popp. 1997. "Theory and practice of pollution credit trading in water quality management." *Review of Agricultural Economics* 19(2):252.

Hogrefe, C., B. Lynn, K. Civerolo, J. Ku, J. Rosenthal, C. Rosenzweig, R. Goldberg, S. Gaffin, K. Knowlton, and P. Kinney. 2004. "Simulating changes in regional air pollution over the eastern United States due to changes in global and regional climate and emissions." *J. Geophys. Res* 109:D22301.

Honjo, T., and T. Takakura. 1991. "Simulation of thermal effects of urban green areas on their surrounding areas." *Energy and Buildings* 15(3-4):443-446.

Jin, M., J.M. Shepherd, and C. Peters-Lidard. 2007. "Development of a parameterization for simulating the urban temperature hazard using satellite observations in climate model." *Natural Hazards* 43(2):257-271.

Just, R.E., D.L. Hueth, and A. Schmitz. 2005. *The welfare economics of public policy: a practical approach to project and policy evaluation*: Edward Elgar Pub.

Kahn, J.R. 2005. "The economic approach to environmental and natural resources."

Keiser, D. 2009. "Examining the Effects of Ecological and Politcal Boundaries on the Potential for Water Quality Trading: Lessons From Two Southeastern Trading Frameworks ".

Köhler, M. 2006. "Long-term vegetation research on two extensive green roofs in Berlin." *Urban Habitats* 4(1):3-25.

Lesser, J.A., D. Dodds, and R.O. Zerbe. 1997. *Environmental economics and policy*: Addison-Wesley.

Liptan, T. 2003. "Planning, zoning and financial incentives for ecoroofs in Portland, Oregon." *Greening Rooftops for Sustainable Communities*:29-30.

Lugo-Amador, N.M., T. Rothenhaus, and P. Moyer. 2004. "Heat-related illness." *Emergency medicine clinics of North America* 22(2):315-328.

Miceli, T.J., and A.P. Minkler. 1995. "Willingness-to-Accept versus Willingness-to-Pay Measures of Value: Implications for Rent Control, Eminent Domain, and Zoning." *Public Finance Review* 23(2):255.

Moran, A., B. Hunt, and G. Jennings. 2004. "A North Carolina field study to evaluate greenroof runoff quantity, runoff quality, and plant growth." *Greening Rooftops for Sustainable Communities*.

Muller, N.Z., and R. Mendelsohn. 2007. "Measuring the damages of air pollution in the United States." *Journal of environmental economics and management* 54(1):1-14.

Muller, N.Z., R. Mendelsohn, and W. Nordhaus. 2011. "Environmental Accounting for Pollution in the United States Economy." *The American Economic Review* 101(5):1649-1675.

Narejo, D. 2010. "Green roof market growth: Opportunities and challenges." *GeoSynthetics* (October,2010). http://geosyntheticsmagazine.com/articles/1010_f4_green_roof.html.

Newswire. 2010. "Green Roof Market Update." *Newswire* (March,2010). http://www.reportlinker.com/p0179580/U-S-Roofing-Market.html

Nguyen, T.N., R.T. Woodward, M.D. Matlock, A. Denzer, and M. Selman. 2006. "A guide to market-based approaches to water quality." *World Resources Institute*.

Niu, H., C. Clark, J. Zhou, and P. Adriaens. 2010. "Scaling of economic benefits from green roof implementation in Washington, DC." *Environmental science & technology* 44(11):4302-4308.

Oberndorfer, E., J. Lundholm, B. Bass, R.R. Coffman, H. Doshi, N. Dunnett, S. Gaffin, M. Köhler, K.K.Y. Liu, and B. Rowe. 2007. "Green roofs as urban ecosystems: ecological structures, functions, and services." *Bioscience* 57(10):823-833.

Oke, T. 1981. "Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observations." *International Journal of Climatology* 1(3):237-254.

Oke, T. 1982. "The energetic basis of the urban heat island." *Quarterly Journal of the Royal Meteorological Society* 108(455):1-24.

Oke, T.R. 1973. "City size and the urban heat island." *Atmospheric Environment (1967)* 7(8):769-779.

Pearce, D.W., and R.K. Turner. 1990. *Economics of natural resources and the environment*: Johns Hopkins Univ Pr.

Peck, S.W. 1999. *Greenbacks from green roofs: forging a new industry in Canada*: Canada Mortgage and Housing Corporation.

Pledge, E. 2005. *Green Roofs: Ecological Design and Construction*: Schiffer Pub.

Popp, D. (2001) Pollution control innovations and the Clean Air Act of 1990, National Bureau of Economic Research Cambridge, Mass., USA.

Portland Bureau of Environmental Services. 2012. City of Portland, Oregon. Ecoroof Incentives. http://www.portlandonline.com/bes/index.cfm?c=48724

Randall, A. 1987. "Resource economics: an economic approach to natural resource and environmental policy."

Rizwan, A.M., L.Y.C. Dennis, and C. Liu. 2008. "A review on the generation, determination and mitigation of Urban Heat Island." *Journal of Environmental Sciences* 20(1):120-128.

Rosenfeld, A.H., H. Akbari, S. Bretz, B.L. Fishman, D.M. Kurn, D. Sailor, and H. Taha. 1995. "Mitigation of urban heat islands: materials, utility programs, updates." *Energy and Buildings* 22(3):255-265.

Rosenzweig, C., W.D. Solecki, and R. Slosberg. 2006. "Mitigating New York City's heat island with urban forestry, living roofs, and light surfaces." *A report to the New York State Energy Research and Development Authority*.

Saito, I., O. Ishihara, and T. Katayama. 1991. "Study of the effect of green areas on the thermal environment in an urban area." *Energy and Buildings* 15(3-4):493-498.

Santamouris, M., N. Papanikolaou, I. Livada, I. Koronakis, C. Georgakis, A. Argiriou, and D. Assimakopoulos. 2001. "On the impact of urban climate on the energy consumption of buildings." *Solar Energy* 70(3):201-216.

Semenza, J.C., J.E. McCullough, W.D. Flanders, M.A. McGeehin, and J.R. Lumpkin. 1999. "Excess hospital admissions during the July 1995 heat wave in Chicago." *American Journal of Preventive Medicine* 16(4):269-277.

Takebayashi, H., and M. Moriyama. 2009. "Study on the urban heat island mitigation effect achieved by converting to grass-covered parking." *Solar Energy* 83(8):1211-1223.

The Atlanta Journal-Constitution. 2010.Peek behind Georgia Power's giant grid. http://www.ajc.com/business/peek-behind-georgia-powers-553118.html.

The Federal Reserve Bank of Minneapolis, Community & Education. 2011. Consumer Price Index, 1913-. http://www.minneapolisfed.org/community_education/teacher/calc/hist1913.cfm.

Thompson, M. 2008. "ICT and development studies: towards development 2.0." *Journal of International Development* 20(6):821-835.

Tol, R.S.J. 2005. "The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties." *Energy policy* 33(16):2064-2074.

United Nations, United Nations Department of Economic and Social Affairs Population Division, Population Estimates and Projections Section. 2012. World Urbanization "Prospects, the 2011 Revision". http://esa.un.org/unpd/wup/pdf/WUP2011_Highlights.pdf.

VanWoert, N.D., D.B. Rowe, J.A. Andresen, C.L. Rugh, R.T. Fernandez, and L. Xiao. 2005. "Green Roof Stormwater Retention-- Effects of Roof Surface, Slope, and Media Depth." *Journal of environmental quality* 34(3):1036-1044.

VanWoert, N.D.R., D.B. Andresen, J.A. Rugh, C.L. Fernandez, and R.T. Xiao. 2005. "Green Roof Stormwater Retention." *Journal of environmental quality* 34(3):1036.

Weiler, S.K., and K. Scholz-Barth. 2009. *Green roof systems: a guide to the planning, design, and construction of landscapes over structure*: Wiley.

World Health Organization, Media Center.2011. "Air Quality and Health." http://www.who.int/mediacentre/factsheets/fs313/en/

Williams, N.S.G., J.P. Rayner, and K.J. Raynor. 2010. "Green roofs for a wide brown land: Opportunities and barriers for rooftop greening in Australia." *Urban Forestry & Urban Greening* 9(3):245-251.

Won Kim, C., T.T. Phipps, and L. Anselin. 2003. "Measuring the benefits of air quality improvement: a spatial hedonic approach." *Journal of environmental economics and management* 45(1):24-39.

Yok Tan, P., and A. Sia (2005) A pilot green roof research project in Singapore, pp. 4–6.

Zhou, Y., and J.M. Shepherd. 2010. "Atlanta's urban heat island under extreme heat conditions and potential mitigation strategies." *Natural Hazards* 52(3):639-668.

U.S. Department of Commerce, Census Bureau. 2012. State & County QuickFacts. http://quickfacts.census.gov/qfd/states/13/1304000.html.

U.S. Department of Energy, Building Energy Databook. 2006. US Department of Energy an Annual Energy Review 2007. DOE/EIA-0384. http://www.epa.gov/greenbuilding/pubs/gbstats.pdf.

U.S. Department of Energy, Energy Efficiency and Renewal Energy. 2011. Federal Technology Alert. A New Technology Demonstration Publication. DOE/EE-0298. Green Roofs. http://www1.eere.energy.gov/femp/pdfs/fta_green_roofs.pdf.

U.S. Department of Energy, EnergyPlus Energy Simulation Software.2011a. http://apps1.eere.energy.gov/buildings/energyplus/energyplus_about.cfm

U.S. Energy Information Administration, SEDS. 2011. State Energy Data System. http://www.eia.gov/state/seds/sedsstates.cfm?q_state_a=GA&q_state=Geor gia.

U.S Environmental Protection Agency, Green Book. 2012. Currently Designated Nonattainment Areas for All Criteria Pollutants. http://www.epa.gov/oaqps001/greenbk/ancl.html.

U.S. Environmental Protection Agency, Energy Star. 2011a. Portfolio Manager. http://www.energystar.gov/index.cfm?c=evaluate_performance.bus_portfoli omanager.

Note: All calculations are adjusted to 2011 constant dollars.

Table 4.35: 40 Years Detailed Cost-Benefit under M1F4H0

Cost Benefit Comparison									
Category	**CR Private Cost**	**CR Public Cost**	**CR Total Cost**	**GR Private Cost**	**GR Public Cost**	**GR Total Cost**	**GR Private Benefit**	**GR Public Benefit**	**GR total Benefit**
Installation	31,978,744		31,978,744	40,730,828		40,730,828	-8,752,083		-8,752,083
Maintenance	5,331,312		5,331,312	27,010,568		27,010,568	-21,679,256		-21,679,256
Energy	335,745,064		335,745,064	313,183,269		313,183,269	22,561,794		22,561,794
Stormwater Fee	1,621,740		1,621,740	567,609		567,609	1,054,131		1,054,131
Stormwater Infra		2,965,021	2,965,021		1,037,757	1,037,757		1,927,263	1,927,263
Healthcare		131,581,309	131,581,309		126,030,776	126,030,776		5,550,533	5,550,533
Health Care Effect due to Energy use, tracking back to plants		534,708	534,708		493,015	493,015		41,693	41,693
Total	374,676,861	135,081,038	509,757,898	381,492,274	127,561,548	509,053,822	-6,815,413	7,519,490	704,076
Total w/o maintenance	369,345,548		504,426,586	354,481,706		482,043,254	14,863,842		22,383,332
Total w/o stormwater	373,055,120		508,136,158	380,924,665		507,448,456	-7,869,544		-350,055

Table 4.36: 40 Years Detailed Cost-Benefit under M1F3H0

Cost Benefit Comparison									
Category	**CR Private Cost**	**CR Public Cost**	**CR Total Cost**	**GR Private Cost**	**GR Public Cost**	**GR Total Cost**	**GR Private Benefit**	**GR Public Benefit**	**GR total Benefit**
Installation	31,978,744		31,978,744	40,730,828		40,730,828	-8,752,083		-8,752,083
Maintenance	5,331,312		5,331,312	27,010,568		27,010,568	-21,679,256		-21,679,256
Energy	335,745,064		335,745,064	317,431,751		317,431,751	18,313,313		18,313,313
Stormwater Fee	1,621,740		1,621,740	567,609		567,609	1,054,131		1,054,131
Stormwater Infra		2,965,021	2,965,021		1,037,757	1,037,757		1,927,263	1,927,263
Healthcare		131,581,309	131,581,309		126,030,776	126,030,776		5,550,533	5,550,533
Health Care Effect due to Energy use, tracking back to plants		534,708	534,708		498,868	498,868		35,840	35,840
Total	374,676,861	135,081,038	509,757,898	385,740,755	127,567,401	513,308,156	-11,063,895	7,513,637	-3,550,258
Total w/o Maintenance	369,345,548		504,426,586	358,730,187		486,297,588	10,615,361		18,128,998
Total w/o stormwater	373,055,120		508,136,158	385,173,146		511,702,790	-12,118,026		-4,604,389

Table 4.37: 40 Years Detailed Cost-Benefit under M1F2H0

Cost-Benefit Comparison									
Category	**CR Private Cost**	**CR Public Cost**	**CR Total Cost**	**GR Private Cost**	**GR Public Cost**	**GR Total Cost**	**GR Private Benefit**	**GR Public Benefit**	**GR total Benefit**
Installation	31,978,744		31,978,744	40,730,828		40,730,828	-8,752,083		-8,752,083
Maintenance	5,331,312		5,331,312	27,010,568		27,010,568	-21,679,256		-21,679,256
Energy	335,745,064		335,745,064	322,384,841		322,384,841	13,360,223		13,360,223
Stormwater Fee	1,621,740		1,621,740	567,609		567,609	1,054,131		1,054,131
Stormwater Infra		2,965,021	2,965,021		1,037,757	1,037,757		1,927,263	1,927,263
Healthcare		131,581,309	131,581,309		126,030,776	126,030,776		5,550,533	5,550,533
Health Care Effect due to Energy use, tracking back to plants		534,708	534,708		506,322	506,322		28,385	28,385
Total	374,676,861	135,081,038	509,757,898	390,693,846	127,574,856	518,268,701	-16,016,985	7,506,182	-8,510,803
Total w/o Maintenance	369,345,548		504,426,586	363,683,278		491,258,133	5,662,271		13,168,453
Total w/o stormwater	373,055,120		508,136,158	390,126,237		516,663,335	-17,071,116		-9,564,934

Table 4.38: 40 Years Detailed Cost-Benefit under M1F1H0

Cost Benefit Comparison									
Category	**CR Private Cost**	**CR Public Cost**	**CR Total Cost**	**GR Private Cost**	**GR Public Cost**	**GR Total Cost**	**GR Private Benefit**	**GR Public Benefit**	**GR total Benefit**
Installation	31,978,744			40,730,828		40,730,828	-8,752,083		-8,752,083
Maintenance	5,331,312			27,010,568		27,010,568	-21,679,256		-21,679,256
Energy	335,745,064			328,827,615		328,827,615	6,917,448		6,917,448
Stormwater Fee	1,621,740			567,609		567,609	1,054,131		1,054,131
Stormwater Infra		2,965,021			1,037,757	1,037,757		1,927,263	1,927,263
Healthcare		131,581,309			126,030,776	126,030,776		5,550,533	5,550,533
Health Care Effect due to Energy use, tracking back to plants		534,708			518,927	518,927		15,781	15,781
Total	374,676,861	135,081,038	509,757,898	397,136,620	127,587,460	524,724,080	-22,459,759	7,493,578	-14,966,182
Total w/o Maintenance	369,345,548		504,426,586	370,126,052		497,713,512	-780,504		6,713,074
Total w/o stormwater	373,055,120		508,136,158	396,569,011		523,118,714	-23,513,891		-16,020,313

Table 4.39: 40 Years Detailed Cost-Benefit under M2F4H0

Cost Benefit Comparison									
Category	**CR Private Cost**	**CR Public Cost**	**CR Total Cost**	**GR Private Cost**	**GR Public Cost**	**GR Total Cost**	**GR Private Benefit**	**GR Public Benefit**	**GR total Benefit**
Installation	63,743,737		63,743,737	60,804,015		60,804,015	2,939,722		2,939,722
Maintenance	5,331,312		5,331,312	27,010,568		27,010,568	-21,679,256		-21,679,256
Energy	335,745,064		335,745,064	294,489,211		294,489,211	41,255,853		41,255,853
Stormwater Fee	1,621,740		1,621,740	567,609		567,609	1,054,131		1,054,131
Stormwater Infra		2,965,021	2,965,021		1,037,757			1,927,263	1,927,263
Healthcare		131,581,309	131,581,309		126,030,776			5,550,533	5,550,533
Health Care Effect due to Energy use, tracking back to plants		534,708	534,708		457,370	457,370		77,337	77,337
Total	406,441,854	135,081,038	541,522,891	382,871,403	127,525,904	510,397,307	23,570,450	7,555,134	31,125,584
Total w/o Maintenance	401,110,541		536,191,579	355,860,835		483,386,739	45,249,706		52,804,840
Total w/o stormwater	404,820,113		539,901,151	382,303,794		508,791,940	22,516,319		30,071,453

Table 4.40: 40 Years Detailed Cost-Benefit under M2F3H0

Cost-Benefit Comparison									
Category	**CR Private Cost**	**CR Public Cost**	**CR Total Cost**	**GR Private Cost**	**GR Public Cost**	**GR Total Cost**	**GR Private Benefit**	**GR Public Benefit**	**GR total Benefit**
Installation	63,743,737		63,743,737	60,804,015		60,804,015	2,939,722		2,939,722
Maintenance	5,331,312		5,331,312	27,010,568		27,010,568	-21,679,256		-21,679,256
Energy	335,745,064		335,745,064	302,257,863		302,257,863	33,487,201		33,487,201
Stormwater Fee	1,621,740		1,621,740	567,609		567,609	1,054,131		1,054,131
Stormwater Infra		2,965,021	2,965,021		1,037,757			1,927,263	1,927,263
Healthcare		131,581,309	131,581,309		126,030,776	126,030,776		5,550,533	5,550,533
Health Care Effect due to Energy use, tracking back to plants		534,708	534,708		468,227	468,227		66,481	66,481
Total	406,441,854	135,081,038	541,522,891	390,640,055	127,536,760	518,176,815	15,801,798	7,544,277	23,346,076
Total w/o Maintenance	401,110,541		536,191,579	363,629,487		491,166,247	37,481,054		45,025,331
Total w/o stormwater	404,820,113		539,901,151	390,072,446		516,571,449	14,747,667		22,291,945

Table 4.41: 40 Years Detailed Cost-Benefit under M2F2H0

Cost Benefit Comparison									
Category	**CR Private Cost**	**CR Public Cost**	**CR Total Cost**	**GR Private Cost**	**GR Public Cost**	**GR Total Cost**	**GR Private Benefit**	**GR Public Benefit**	**GR total Benefit**
Installation	63,743,737		63,743,737	60,804,015		60,804,015	2,939,722		2,939,722
Maintenance	5,331,312		5,331,312	27,010,568		27,010,568	-21,679,256		-21,679,256
Energy	335,745,064		335,745,064	311,314,942		311,314,942	24,430,121		24,430,121
Stormwater Fee	1,621,740		1,621,740	567,609		567,609	1,054,131		1,054,131
Stormwater Infra		2,965,021	2,965,021		1,037,757			1,927,263	1,927,263
Healthcare		131,581,309	131,581,309		126,030,776	126,030,776		5,550,533	5,550,533
Health Care Effect due to Energy use, tracking back to plants		534,708	534,708		482,055	482,055		52,653	52,653
Total	406,441,854	135,081,038	541,522,891	399,697,135	127,550,588	527,247,723	6,744,719	7,530,449	14,275,168
Total w/o Maintenance	401,110,541		536,191,579	372,686,566		500,237,155	28,423,975		35,954,424
Total w/o stormwater	404,820,113		539,901,151	399,129,525		525,642,356	5,690,588		13,221,037

Table 4.42: 40 Years Detailed Cost-Benefit under M2F1H0

Cost Benefit Comparison									
Category	**CR Private Cost**	**CR Public Cost**	**CR Total Cost**	**GR Private Cost**	**GR Public Cost**	**GR Total Cost**	**GR Private Benefit**	**GR Public Benefit**	**GR total Benefit**
Installation	63,743,737		63,743,737	60,804,015		60,804,015	2,939,722		2,939,722
Maintenance	5,331,312		5,331,312	27,010,568		27,010,568	-21,679,256		-21,679,256
Energy	335,745,064		335,745,064	323,096,015		323,096,015	12,649,048		12,649,048
Stormwater Fee	1,621,740		1,621,740	567,609		567,609	1,054,131		1,054,131
Stormwater Infra		2,965,021	2,965,021		1,037,757			1,927,263	1,927,263
Healthcare		131,581,309	131,581,309		126,030,776	126,030,776		5,550,533	5,550,533
Health Care Effect due to Energy use, tracking back to plants		534,708	534,708		505,435	505,435		29,272	29,272
Total	406,441,854	135,081,038	541,522,891	411,478,208	127,573,968	539,052,176	-5,036,354	7,507,069	2,470,715
Total w/o Maintenance	401,110,541		536,191,579	384,467,640		512,041,608	16,642,901		24,149,971
Total w/o stormwater	404,820,113		539,901,151	410,910,599		537,446,810	-6,090,485		1,416,584

Table 4.43: 40 Years Detailed Cost-Benefit under M3F4H0

Cost-Benefit Comparison									
Category	**CR Private Cost**	**CR Public Cost**	**CR Total Cost**	**GR Private Cost**	**GR Public Cost**	**GR Total Cost**	**GR Private Benefit**	**GR Public Benefit**	**GR total Benefit**
Installation	85,382,974		85,382,974	80,198,399		80,198,399	5,184,575		5,184,575
Maintenance	5,331,312		5,331,312	27,010,568		27,010,568	-21,679,256		-21,679,256
Energy	335,745,064		335,745,064	327,687,280		327,687,280	8,057,784		8,057,784
Stormwater Fee	1,621,740		1,621,740	567,609		567,609	1,054,131		1,054,131
Stormwater Infra		2,965,021	2,965,021		1,037,757	1,037,757		1,927,263	1,927,263
Healthcare		131,581,309	131,581,309		126,030,776	126,030,776		5,550,533	5,550,533
Health Care Effect due to Energy use, tracking back to plants		534,708	534,708		519,817	519,817		14,890	14,890
Total	428,081,091	135,081,038	563,162,128	435,463,856	127,588,350	563,052,207	-7,382,766	7,492,687	109,921
Total w/o Maintenance	422,749,778		557,830,816	408,453,288		536,041,639	14,296,490		21,789,177
Total w/o stormwater	426,459,350		561,540,388	434,896,247		561,446,840	-8,436,897		-944,210

Table 4.44: 40 Years Detailed Cost-Benefit under M3F3H0

Cost-Benefit Comparison									
Category	**CR Private Cost**	**CR Public Cost**	**CR Total Cost**	**GR Private Cost**	**GR Public Cost**	**GR Total Cost**	**GR Private Benefit**	**GR Public Benefit**	**GR total Benefit**
Installation	85,382,974		85,382,974	80,198,399		80,198,399	5,184,575		5,184,575
Maintenance	5,331,312		5,331,312	27,010,568		27,010,568	- 21,679,256		- 21,679,256
Energy	335,745,064		335,745,064	329,204,595		329,204,595	6,540,469		6,540,469
Stormwater Fee	1,621,740		1,621,740	567,609		567,609	1,054,131		1,054,131
Stormwater Infra		2,965,021	2,965,021		1,037,757	1,037,757		1,927,263	1,927,263
Healthcare		131,581,309	131,581,309		126,030,776	126,030,776		5,550,533	5,550,533
Health Care Effect due to Energy use, tracking back to plants		534,708	534,708		521,908	521,908		12,800	12,800
Total	428,081,091	135,081,038	563,162,128	436,981,171	127,590,441	564,571,612	-8,900,080	7,490,597	-1,409,484
Total w/o Maintenance	422,749,778		557,830,816	409,970,603		537,561,044	12,779,175		20,269,772
Total w/o stormwater	426,459,350		561,540,388	436,413,562		562,966,246	-9,954,212		-2,463,615

Table 4.45: 40 Years Detailed Cost-Benefit under M3F2H0

Cost-Benefit Comparison									
Category	**CR Private Cost**	**CR Public Cost**	**CR Total Cost**	**GR Private Cost**	**GR Public Cost**	**GR Total Cost**	**GR Private Benefit**	**GR Public Benefit**	**GR total Benefit**
Installation	85,382,974		85,382,974	80,198,399		80,198,399	5,184,575		5,184,575
Maintenance	5,331,312		5,331,312	27,010,568		27,010,568	-21,679,256		-21,679,256
Energy	335,745,064		335,745,064	330,973,555		330,973,555	4,771,508		4,771,508
Stormwater Fee	1,621,740		1,621,740	567,609		567,609	1,054,131		1,054,131
Stormwater Infra		2,965,021	2,965,021		1,037,757	1,037,757		1,927,263	1,927,263
Healthcare		131,581,309	131,581,309		126,030,776	126,030,776		5,550,533	5,550,533
Health Care Effect due to Energy use, tracking back to plants		534,708	534,708		524,570	524,570		10,138	10,138
Total	428,081,091	135,081,038	563,162,128	438,750,132	127,593,103	566,343,235	-10,669,041	7,487,934	-3,181,107
Total w/o Maintenance	422,749,778		557,830,816	411,739,564		539,332,667	11,010,214		18,498,149
Total w/o stormwater	426,459,350		561,540,388	438,182,523		564,737,869	-11,723,173		-4,235,238

Table 4.46: 40 Years Detailed Cost-Benefit under M3F1H0

Cost-Benefit Comparison									
Category	**CR Private Cost**	**CR Public Cost**	**CR Total Cost**	**GR Private Cost**	**GR Public Cost**	**GR Total Cost**	**GR Private Benefit**	**GR Public Benefit**	**GR total Benefit**
Installation	85,382,974		85,382,974	80,198,399		80,198,399	5,184,575		5,184,575
Maintenance	5,331,312		5,331,312	27,010,568		27,010,568	-21,679,256		-21,679,256
Energy	335,745,064		335,745,064	333,274,546		333,274,546	2,470,517		2,470,517
Stormwater Fee	1,621,740		1,621,740	567,609		567,609	1,054,131		1,054,131
Stormwater Infra		2,965,021	2,965,021		1,037,757	1,037,757		1,927,263	1,927,263
Healthcare		131,581,309	131,581,309		126,030,776	126,030,776		5,550,533	5,550,533
Health Care Effect due to Energy use, tracking back to plants		534,708	534,708		529,072	529,072		5,636	5,636
Total	428,081,091	135,081,038	563,162,128	441,051,123	127,597,605	568,648,728	-12,970,032	7,483,433	-5,486,599
Total w/o Maintenance	422,749,778		557,830,816	414,040,555		541,638,159	8,709,223		16,192,656
Total w/o stormwater	426,459,350		561,540,388	440,483,514		567,043,361	-14,024,163		-6,540,731

4.28: Subsidy Qualifying Roofs (1st Criteria) under M1F4 and M1F3

4.29: Subsidy Qualifying Roofs (1st Criteria) under M1F2 and M1F1

4.30: Subsidy Qualifying Roofs (1st Criteria) under M2F4 and M2F3

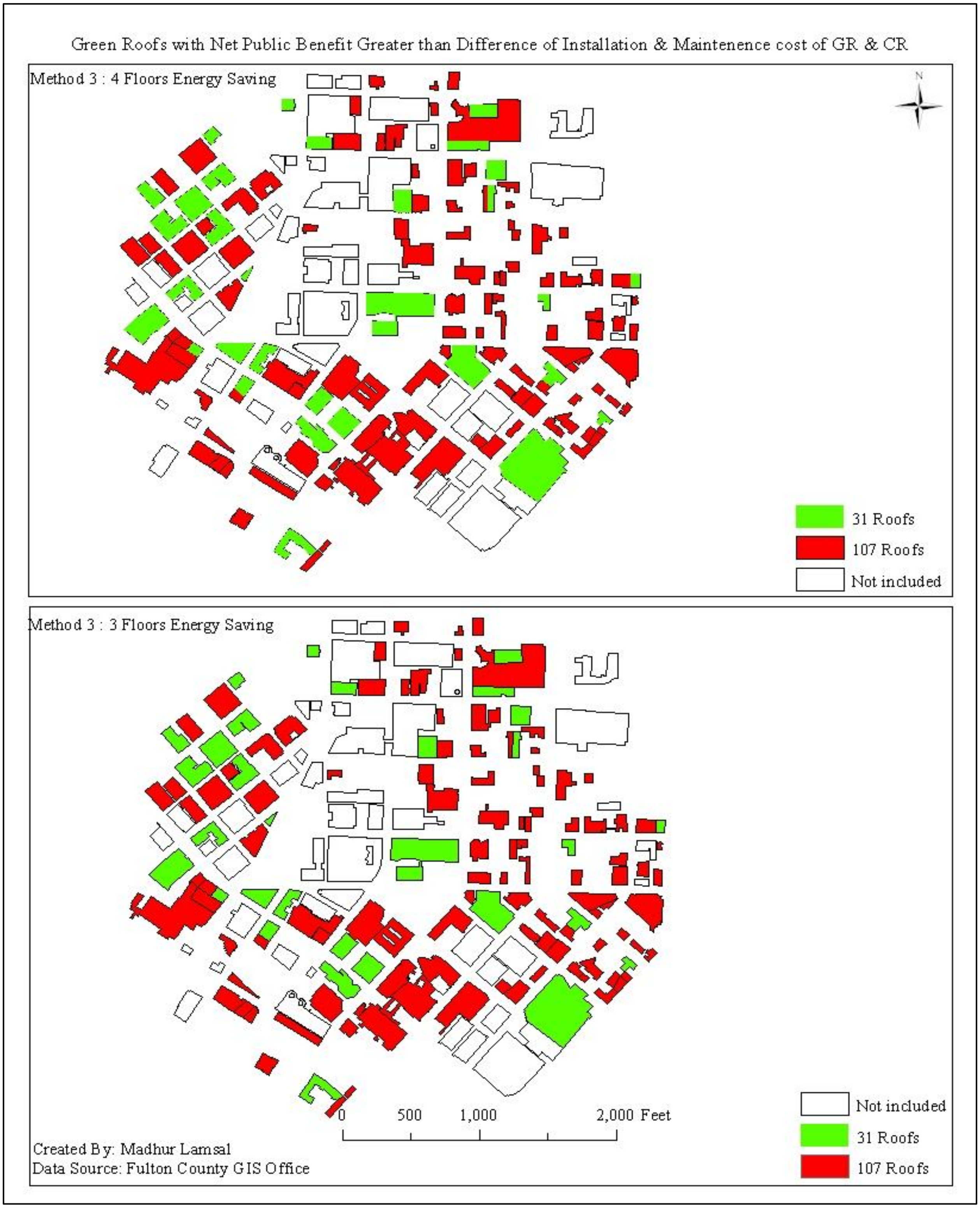
4.31: Subsidy Qualifying Roofs (1st Criteria) under M2F2 and M2F1

4.32: Subsidy Qualifying Roofs (1st Criteria) under M3F4 and M3F3

4.33: Subsidy Qualifying Roofs (1st Criteria) under M3F2 and M3F1

4.34: Public Benefit over Cost Difference of Installation and Maintenance of Conventional and Green roofs under M1F4 and M1F3

4. 35: Public Benefit over Cost Difference of Installation and Maintenance of Conventional and Green roofs under M2F4 and M2F3



4.36: Public Benefit over Cost Difference of Installation and Maintenance of Conventional and Green roofs under M3F4 and M3F3

4.37 Buildings with Higher Social Benefit than Suggested Incentive dollars under M1F4H0

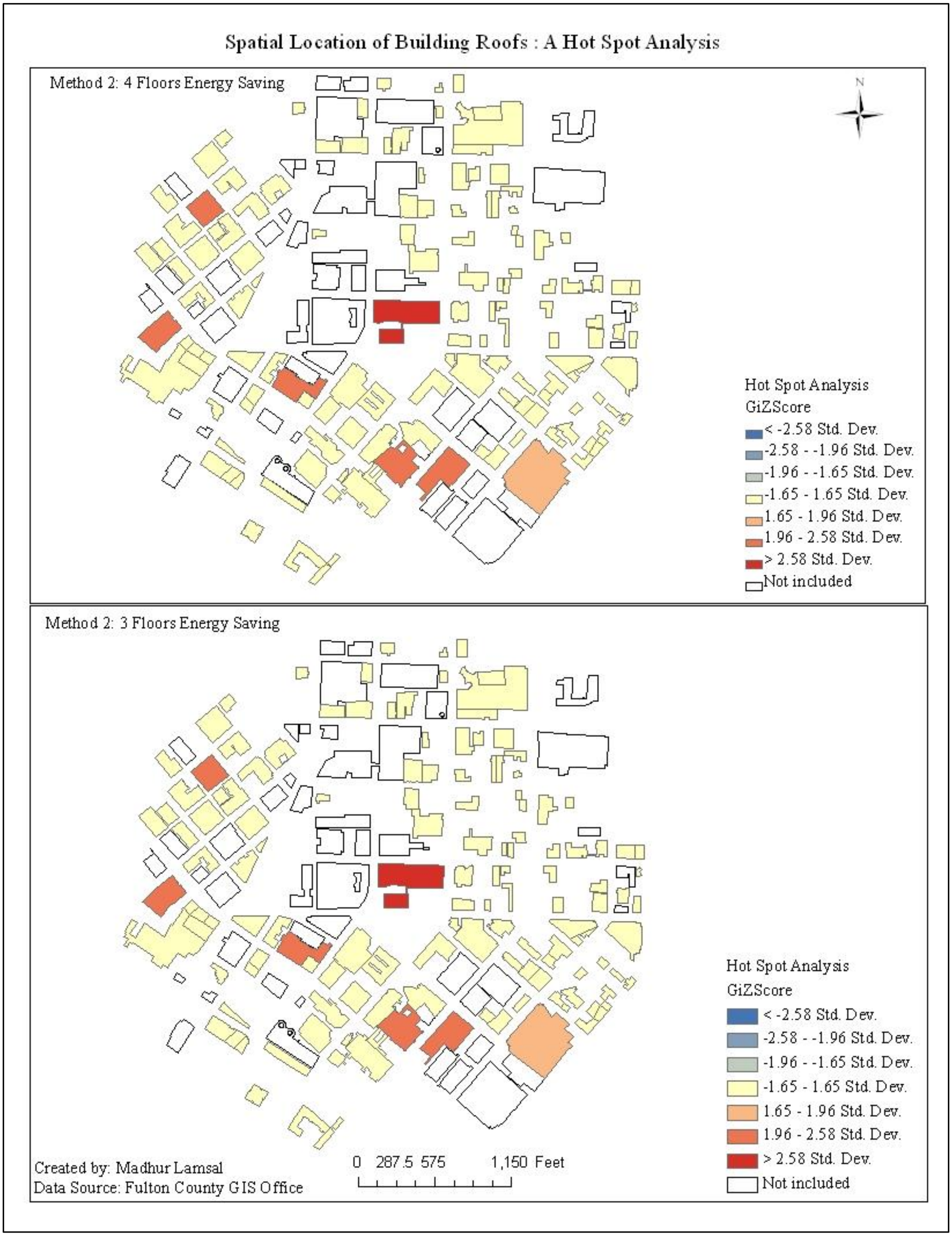
4.38 Buildings with Higher Social Benefit than Suggested Incentive Dollars under M2F4H0

4.39 Buildings with Higher Social Benefit than Suggested Incentive Dollars under M3F4H0

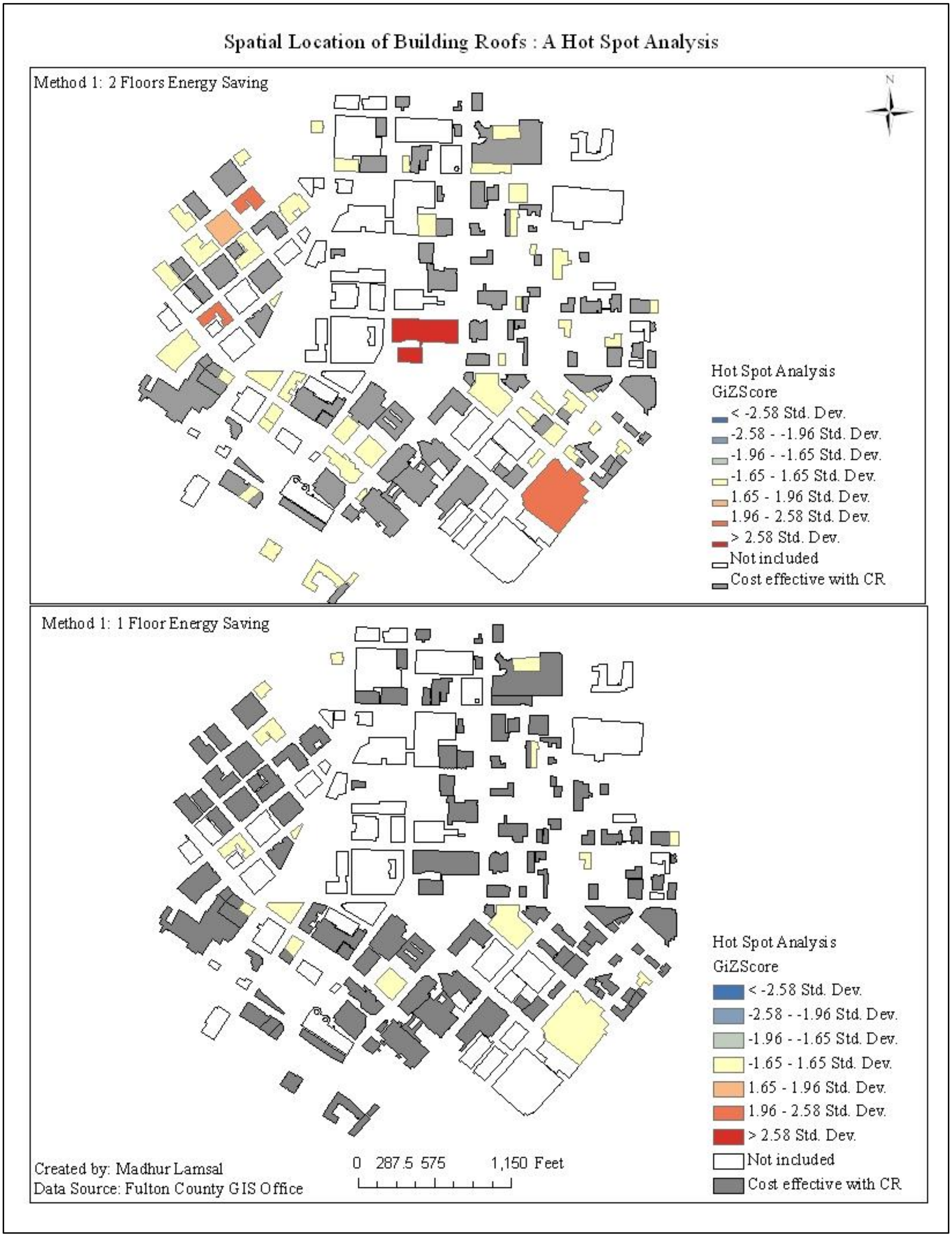
4.40 Buildings with Higher Private Benefit than Suggested Incentive Dollars under M1F4H0

4.41 Buildings with Higher Private Benefit than Suggested Incentive Dollars under M2F4H0

4.42 Buildings with Higher Private Benefit than Suggested Incentive Dollars under M3F4H0



4.43: Hot Spot Analysis Result for M2F4 and M2F3



4.44: Hot Spot Analysis Result under M1F2 and M1F1