Urban Heat Island Mitigation Can Improve New York City's Environment: Research on the Impacts of Mitigation Strategies on the Urban Environment

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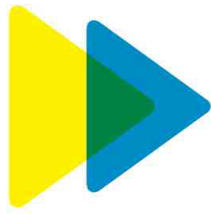
SUSTAINABLE SOUTH BRONX

Urban Heat Island Mitigation Can Improve New York City's Environment:
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Forward

It is a great pleasure for me to contribute to the second Sustainable South Bronx Working Paper, a result of our collaboration with the Columbia University's Cool City Project and Center for Sustainable Urban Development. It reminds me of how far a community like the South Bronx has come and how much further it can go if policymakers would take some of these conclusions to heart and put them into practice. City and state regulatory agencies consistently use antiquated zoning regulations to justify the siting of burdensome facilities such as waste transfer stations and power plants in politically vulnerable, low-income Latino and African-American communities.

When George W. Bush withdrew the U.S. from the Kyoto Protocol, reneging on his own campaign promise to reduce CO2 emissions (a major contributor to climate change) in accord with the fossil fuel industry lobbyists, environmentalists all over the country were understandably outraged. As an Environmental Justice activist in the South Bronx, NYC, I considered it a potential death knell for my community and communities just like it all over the country.

Our examination here of the potential impacts of urban heat island (UHI) mitigation strategies for New York City suggests a new way to approach the business of developing new policies that impact the city in terms of sustainable development. It encourages the creation of an economic development model that does a cost-benefit analysis including the real-world price of improved public health and less tangible quality of life issues such as increased community pride and reduced crime because residents find their communities easier to live in. This line of thinking places an emphasis on the priceless impacts that support the public good – as well as right some historic wrongs – and factors them into a business model.

Simply put, the South Bronx and communities like it have much to lose if the environmental quality of the community does not improve, and implementing green building technologies such as green and cool roofs is but one of the many strategies that can be employed to create positive and lasting environmental change. Such improvements could serve to inform countless communities about how sustainable development can be implemented in even the most trying circumstances. Policies make practices consistent and this effort supports the radical belief that there can be an interplay between social equity, businesses and government so that all concerned can win.

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Founder
Sustainable South Bronx

Preface

There is a need in large cities like New York to study the science and art of sustainable development – to discover what works and what does not work for creating and maintaining healthy, safe and vibrant communities for citizens to live, work and play in. Recent developments in high performance building and urban design techniques, such as the Leadership in Energy and Environmental Design (LEED) Green Building Rating System, seek to maximize the ecological intelligence of the built environment in tangible ways that create healthy and economically viable habitats. To this approach we note that sustainable development implies public actions that are not only efficient and ecologically sound, but also foster economic and environmental justice.

One promising area for environmental improvement in New York City is in the development and application of urban heat island mitigation techniques. These are building and urban fabric modifications that may hold multiple benefits in energy conservation, stormwater retention, aesthetics and air quality; but the costs and benefits of their application in New York City neighborhoods are not yet fully described. It is to begin to assess the impacts of these techniques for interested community groups and residents that this review of the literature on heat island mitigation, particularly cool and green living roofs, is aimed. This research was developed through a unique community-university partnership, between Sustainable South Bronx's (SSBx) Smart Roof Demonstration Project and two groups at Columbia University; the Columbia Earth Institute's Center for Sustainable Urban Development and the Institute for Social and Economic Research and its Cool City Project. It is the second of two Working Papers produced through this partnership on the environmental impacts, costs and benefits of green building techniques for use by Sustainable South Bronx.

We write on these topics from the perspective of urban planners and community advocates, for communities and their residents. The articulation, assessment and implementation of sustainable development techniques is inherently an interdisciplinary exercise, and we welcome reader's feedback on this paper, and comments from readers on ideas and developments in these subjects. The environmental and health impacts of the built environment and urban climate hold special relevance for residents and planners due to the climate's pervasive impacts on energy consumption, human health, infrastructure planning and urban policy, and because of the built environment's effects on urban climate. We seek the continued guidance and support of the engineers, meteorologists, chemists, hydrologists, and other technical experts whose work is central to the development of a sustainable urban environment and whose research informed this report. However, the issues of urban environmental quality and policy are too important to leave only to technical specialists to discuss and decide. Per Dr. Barry Commoner, environmental policy is better served if guided, instead, by the words of Thomas Jefferson:

> I know of no safe depository of the ultimate powers of society but the people themselves….and if we think them not enlightened enough to exercise their control with a wholesome discretion, the remedy is not to take it from them, but to inform their discretion. (Ford 1892-99).

Acknowledgements

Introduction

Eager astonishment," wrote columnist Kate Buss in 1927, was her temperament after contemplating "why miles of roofs are permitted to be so unused and so ugly while resourceful city planners seek the difficult and the costly means to give fresh air to the citizens and to ornament a city's perspective." Today Ms. Buss undoubtedly would remain in a state of 'eager astonishment,' as most rooftops are neither better utilized nor more aesthetically pleasing than they were 80 years ago.

This report discusses green "living" roofs and "cool" highly reflective roofs -- building technologies that may offer solutions to ameliorate the problems Ms. Buss enumerates, and other urban problems as well. There is a need for a better understanding of the specific costs and benefits of green building techniques such as living roofs in urban areas. Towards this end, this report has a relatively narrow goal; to focus on why these particular techniques may be incorporated into strategies for urban heat island mitigation, we review research assessing their environmental impacts. We discuss the literature describing the effects of these "smart" rooftops on ambient air temperatures, energy use, and air quality. We briefly review cost-benefit analyses of these strategies and provide some initial insight into why urban heat island mitigation should be encouraged in New York City in light of these findings.

1.1 What is an urban heat island?

An urban heat island (UHI) is an urban area with higher surface and near-surface air temperatures than its surrounding suburban and rural areas. The UHI effect exists due to the greater heat retention of buildings and man-made surfaces such as concrete and asphalt, ubiquitous in cities, compared to the lesser heat retention and cooling properties of vegetation, which is more abundant in the countryside. Urban streets typically have fewer trees and other vegetation to shade buildings and cool the air by evapotranspiration. As a result, urbanized land cover tends to retain less surface water from precipitation than natural land cover. The urban heat island temperature effect can be measured in terms of the urban canopy layer, which refers to the space below the rooftops of buildings, and the mesoscale, which refers to regional temperature measurement (Voogt, 2002). Figure 1 is a popularly used depiction of a "typical" heat island effect on near-ground temperature.

Figure 1. Sketch of an Urban Heat Island Profile
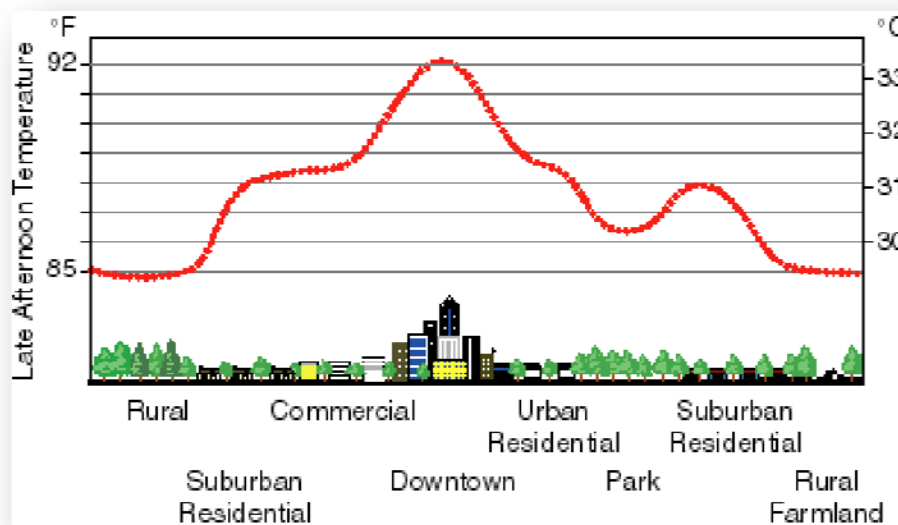
Near-surface air temperature differential between urban and rural areas on a hot and sunny afternoon. Heat Island Group, Lawrence Berkley Laboratories, 2000.

The magnitude of the UHI, in terms of the temperature differential between a city and its surrounding countryside, is greatest during dry, clear, low-wind nights. This occurs because the surfaces that comprise the urban built environment retain and re-radiate more heat into the air at night than vegetation and non-urbanized land cover. Also, the surface geometry and thermal properties of urban built environment's non-vegetative surfaces greatly impact the magnitude of the urban heat island (Voogt, 2002).[1]

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[1] The urban heat island effect, and the impact of a city's land use on its local climate, is a more complex meteorological phenomenon than is discussed in this report. For example, urban land use and form may affect wind speed, cloud cover, precipitation patterns, etc. Our focus is on surface and near-surface air temperature, as that is the meteorological parameter of greatest concern for the urban impacts discussed here, and on interventions to cool the urban fabric. Future studies on New York City and the metropolitan region could include additional variables to more thoroughly evaluate

1.1.2 New York City's urban heat island

The heat island effect has existed in New York City since at least the end of the 19th century. Urban Planning student Monica Pena Sastre (Columbia University) demonstrated that a difference of at least 1.8ºF (1ºC) already existed at the beginning of the 20th century between the mean temperature in NYC and its surrounding rural areas, and this difference increased over the 20th century (Sastre, 2003). Analysis of annual mean temperatures between 1900 – 1997 shows that mean temperatures in New York City (Central Park weather station) were generally higher than that of the surrounding region, ranging from 2.2°F (1.2°C) to 5.4°F (3.0°C) (Rosenthal et al., 2003), and demonstrate a significant decrease in the monthly and seasonal variability of the UHI effect over the century. Gedzelman et al. conclude that from 1997 to 1998, the mean of New York City's heat island was 7.2ºF (4°C) in the summer and fall and 5.4ºF (3°C) in the winter and spring (2003).

1.1.3 New York City and global climate change

New York City has experienced two warming trends during the 20th century: that caused by the urban heat island effect, and the trend caused by global warming of the earth's lower atmosphere. The near-surface air temperature of the 31-county New York metropolitan region warmed about 2ºF (1.1°C) over the past century, according to the Columbia Earth Institute's Metropolitan East Coast study (Rosenzweig & Solecki, 2001). Figure 2 demonstrates the increasing mean temperature of New York City's Central Park weather station over the course of the 20th century (Peña, 2003).

Figure 2. Temperature trends, Central Park, New York, 1876-2000
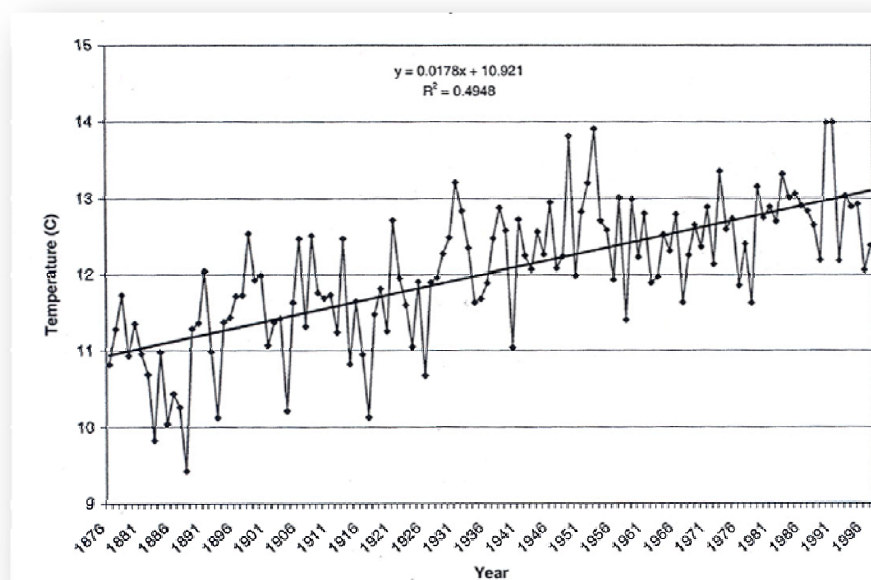
The rise in New York City's Central Park average annual temperature over the 20th century; data not corrected for the UHI effect (Peña, 2003).

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this issue: e.g., wind speed, cloud cover, differences in minimum and maximum temperatures, etc. For further information on UHIs, see Voogt, 2002; on NYC's UHI, see Slosberg et al., 2006.

These trends are expected to increase in the future. Projections of global and regional climate predict a significant increase in average temperatures in New York City due to global environmental change during the next 80 years. The New York Climate & Health Project, an interdisciplinary assessment of regional climate change impacts led by researchers with Columbia University's Mailman School of Public Health and the Columbia Earth Institute, used two possible scenarios of future greenhouse gas emissions to model the impact of global climate change on New York City's average daily summer temperatures (Rosenthal et al., 2004). The climate projections were based on the United Nations Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios (SRES) A2 and B2 greenhouse gas emissions scenarios (Rosenthal et al, 2004, 2).

Using the A2 scenario of high CO_2 emissions (30 gigatons/yr max), projections with the NASA-GISS global climate model predict an increase of 5.4ºF to 6.3ºF (3.0°C to 3.5°C) in average annual temperatures in the city by 2100. Projections using the B2 scenario of medium CO_2 emissions (15 gigatons/yr max) predict an increase by 3.6ºF to 4.5ºF (2.0°C to 2.5°C) by 2100 (Rosenthal et al., 2004). These modeled climate change projections reinforce the importance of adaptive and mitigative planning strategies aimed at decreasing urban temperatures.

New York City's current heat island effect and the potential for increased summertime temperatures due to climate change are cause for concern. Currently of concern to public officials is the city's summertime peak energy demand due to high urban temperatures (Kerr, 2004). Increased peak demand for electricity creates higher levels of power plant emissions and the need to plan for additional generating capacity. Increased power plant emissions and levels of ambient air pollutants such as nitrogen oxides and volatile organic compounds, coupled with high urban temperatures, result in increased ozone levels. High levels of air pollution, including but not limited to ozone, present a substantial threat to the health of urban populations, as do extreme summertime temperatures that the heat island effect exacerbates (Kinney, 1999; Kalkstein, 2002). Additionally, power plants emit greenhouse gases which further contribute to the atmospheric changes that lead to global warming.

1.2.2   NYC's urban heat island and heat-related ozone levels

Ground-level ozone (O_3), a principal component of smog, forms when ultraviolet solar radiation reacts with nitrogen oxides (NO_x) and volatile organic compounds (VOCs) from power plants, automobiles, industrial sources and certain kinds of vegetation in the lower atmosphere. Automobile combustion, which emits NO_x, VOCs, and CO, contributes substantially to the formation of ozone (Elsom, 2002). The photochemical reactions that form ground-level ozone are more likely to occur and intensify as temperatures increase (Heat Island Group, 2000). Reflecting the role of summertime heat in the formation of ozone, one study has documented that for every 1°F (.6ºC) increase in temperature above 70°F (21ºC), a 3% increase in ozone levels occurs in Los Angeles (Heat Island Group, 2000). Figure 3, published by the US Global Change Research Program, demonstrates a similar correlation between ozone concentration and maximum temperatures in New York City.

Figure 3. Maximum Daily Ozone Concentrations vs. Maximum Temperature, New York City
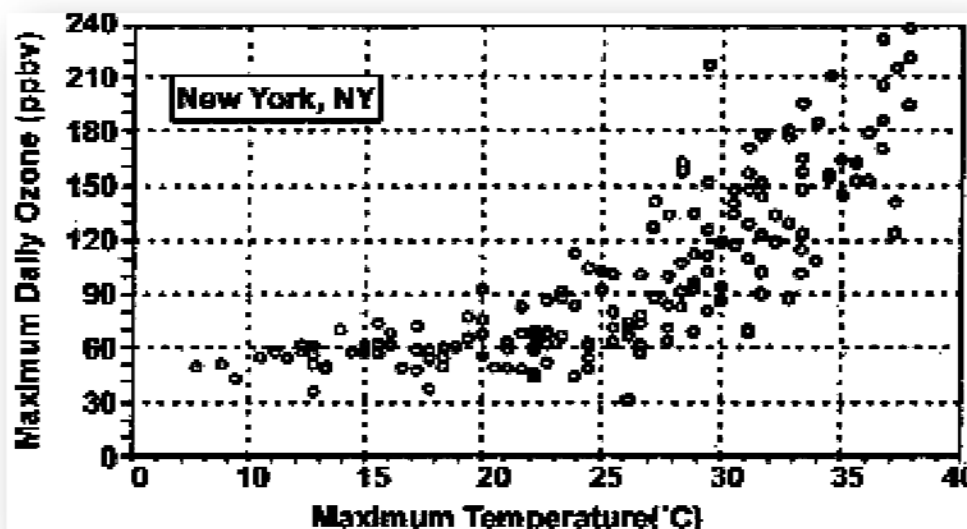
Ground Level Ozone Concentrations vs. Temperature, as observed from May to October 1988-1990. From National Assessment Synthesis Team, 2000.

Fisk (2005) looked at mean hourly temperature from 1962-1992 and found that from mid-May through late September, the average 2:00 p.m. ambient air temperature reached over 70ºF (21ºC). Therefore, during a significant portion of the year— at least 130 days— there may be increased ozone levels due in part to higher temperatures (Fisk, 2005). As summer season temperatures increase over time, due to global climate change, an expanded urban heat island effect in the New York metropolitan region, or interactions between these two types of environmental change, more days in New York City may have daily average temperatures exceeding 70ºF which may in turn increase ozone concentrations.

Impacts of the urban heat island effect are also manifested at the regional level. Due to the time delay between ozone precursor emmitance (from automobiles early in the morning during rush hour) and when most ozone formation occurs (later in the day, with peak solar radiation), areas downwind of high-traffic areas—generally suburban regions surrounding city centers —frequently have the highest ozone levels in a given region (Elsom, 2002).

Figure 4. NYC Energy Use vs. Temperature, 2003
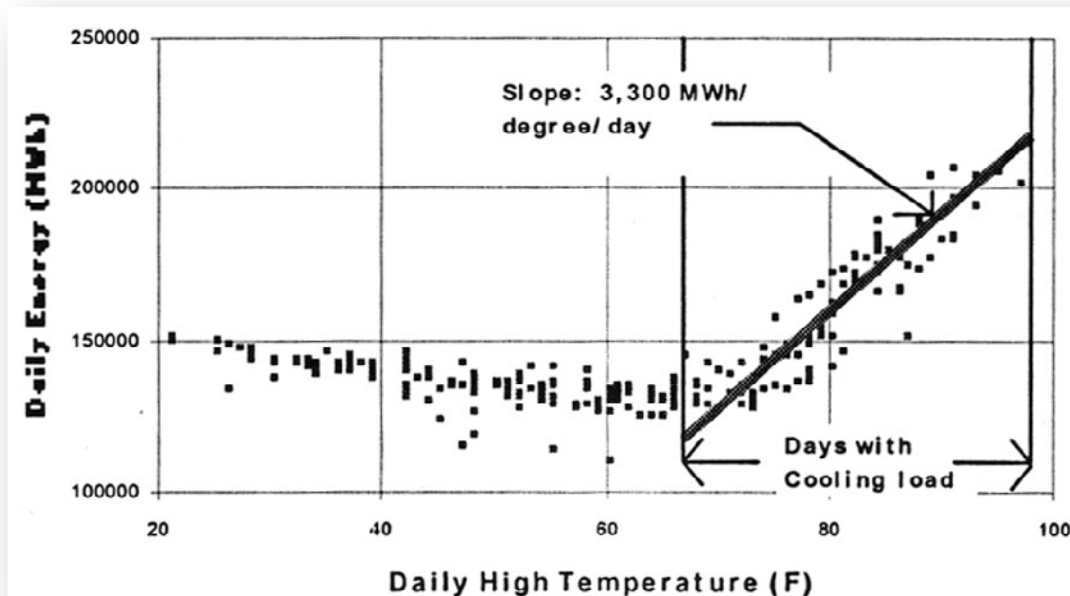
Kerr and Yao of NYC's Office of Sustainable Design plotted the relationship between energy use and daily high temperature, demonstrating an increase in energy use as temperatures rise above 68ºF (20ºC). From Kerr and Yao, unpublished draft, 2004. Printed with permission of authors.

1.2.3   Public health impacts of the urban heat island effect

In addition to increased energy consumption, the heat island effect increases the impacts of high summer temperatures on public health. This problem has been recognized for decades. Buechley et al. (1972) discuss the higher mortality rate in New York City compared to its suburbs during the deadly heat wave of 1966. The increased night-time temperatures created by the heat island effect increase the risk of heat-related mortality in urban neighborhoods.

Air pollution and heat stress are important current public health stressors in many urban areas across the US, and both are strongly affected by temperature and climate variability. Extreme heat events especially endanger the health and well-being of elderly and poor urban residents. Excessive exposure to high heat can bring about injury, disease or death if the body is not able to cool down and shed excess heat (USDHHS, 1992).

In New York, as in other cities around the world, summertime heat can lead to elevated mortality and morbidity rates, especially during the extended periods of hot weather known as heat waves. Since 1998, summertime heat has been the top weather-related cause of mortality in the United States (NOAA, 2008). Numerous epidemiology studies have examined the relationship between extreme heat events and increases in short-term mortality in urban populations in the temperate zone (Kalkstein and Greene, 1997; McGeehin and Mirabelli, 2001; Braga et al., 2002).

The epidemiological literature has identified factors in the built environment and demographic characteristics that can increase the risk of heat-related mortality. The elderly and people with pre-existing illnesses are especially vulnerable populations; other risk factors include being bedridden, living alone, and having poor access to public transportation or air-conditioned neighborhood places (Semenza et al., 1996). Analysis of the Chicago 1995 heat wave, which led to over 700 deaths, showed that risk of heat-related mortality was higher in the black community and for people living in certain types of low-income and multi-tenant housing, including living on the top floors of buildings (Klinenberg, 2002). Chicago's experience points to similar vulnerabilities in New York City's population. High spring and summer temperatures also result in increased heat stress and higher daily mortality rates in New York City (Curriero et al., 2002). Public health researchers have estimated that there are over 300 heat-related excess deaths in New York City during an average summer (Kalkstein and Greene, 1997).

Indirectly, the higher temperatures associated with the heat island effect impact public health through increased ambient air pollutants. Higher temperatures accelerate the formation of harmful smog, as ozone precursors combine faster to produce ground-level ozone. Ozone has been found to exacerbate respiratory symptoms and diseases by damaging lung tissue, reducing lung function, and sensitizing the lungs to other irritants (Kinney, 1999; Abelsohn, et al., 2002; Patz, 2001). Ozone air pollution can trigger or exacerbate asthma attacks, reduce lung growth and function, and "may actually lead to the development of asthma in children, as opposed to simply exacerbating existing disease (NRDC, 2004; Koren, 1995; McConnell et al., 2002; Thurston and Ito, 1999)." Elevated ozone conditions have also been shown to increase acute mortality rates, as well as increase hospital admissions for asthma and cardiovascular causes (Koken et al., 2003; Kinney, 1999; Thurston and Ito, 1999).

The higher temperatures caused by the urban heat island increase demand for cooling energy in commercial and residential buildings in summer, increasing the power plant emissions. Other air pollutants generated by power plants, such as particulate matter, carbon monoxide, sulfur dioxide and nitrogen oxides can also damage lung tissue, irritate lungs, and aggravate breathing problems, respiratory illness, and cardiovascular disease (Kinney, 1999; Amdur et al., 1991).

The research of the New York Climate & Health Project suggests that these public health impacts within the metropolitan region could worsen during the 21st century due to a changing climate, increasing heat-related mortalities by more than 55% by the 2020's (Rosenthal et al., 2004). Additionally, the research suggests that estimated increases in ozone concentrations caused by

global warming could lead to a 4.5% increase in ozone-related mortality in the region by the 2050s (Knowlton et al., 2004).

Possible municipal adaptive responses to protect vulnerable populations from heat-related health effects have included: access to air conditioned places, use of heat and air quality health-alert systems, and environmental modifications that can provide an effective and passive approach for reducing the risk of heat stress (Smoyer and Rainham, 2001). The benefits of green roof infrastructure in lowering ambient air temperature and reducing indoor temperatures in residences lacking air conditioners should provide a beneficial intervention for protection of public health from heat and air quality related health impacts.

Fortunately, effective UHI mitigation strategies exist to ameliorate the impacts of the urban heat island effect. This section examines some research on the potential benefits of strategies to change the surface properties of the built environment to reduce temperature gain from the heat island effect.

These methods depend primarily on changing two properties of the urban environment: increasing urban vegetation and increasing the albedo, or reflectivity, of surfaces. Adding street trees and trees that shade buildings from solar radiation are the most common ways of increasing urban vegetation to mitigate the UHI. Living vegetative systems placed on a roof (known as green roofs) can also reduce a building's heat gain. As green roof systems are a relatively new technology in the United States, other forms of UHI mitigation techniques have been studied in the US to a greater extent. Additionally, their high installation cost, starting at approximately $12 to 25 per square foot in New York City, has been one reason that relatively few studies have been performed by the federal government, city agencies and private researchers to better understand their costs, impacts and benefits (Acks, 2006; L. Kerr, personal communication, April, 2005; H. Taha, personal communication, March, 2005; E. Wong, personal communication, February, 2005). Nevertheless, because roofs occupy an estimated 19% of the city's surface area, and 11% are flat roofs, the easiest kind on which to construct a green roof, this technology warrants increased study as an UHI mitigation technique (Solecki et al., 2006).

"Cool" highly reflective roofing materials and cool pavements also can mitigate the UHI effect. Cool roofing technology is currently better understood and developed than cool pavement technology.[2] The cost of cool roofs is less prohibitive than the cost of green roofs, starting at less than $2 per square foot for material. The following section describes several UHI mitigation techniques, focusing on rooftop measures and their respective benefits.

2.1.2   The role of albedo and Solar Reflectance Index (SRI) in urban temperatures

In the summer, materials become hot by absorbing and retaining solar energy. Most commonly, the heat capacity of a given material is measured in terms of its albedo, which is the measure of a material's reflectance. Albedo is measured on a scale from 0 to 1, with 0 signifying that a material does not reflect any solar energy and 1 signifying that a material reflects all solar energy. Figure 5 demonstrates the albedo of various materials common to urban environments (EPA, 2005a).

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[2] For further information on cool paving materials, please see: the EPA Heat Island Reduction Initiative's web site (EPA, 2007d) at http://www.epa.gov/heatisland/strategies/coolpavement.html, the Initiative's draft *Cool Pavement Report* (Cambridge Systematics, Inc, 2005) at http://www.epa.gov/heatisland/resources/pdf/CoolPavementReport_Former%20Guide_complete.pdf, and the Houston Advanced Research Center's *Cool Houston!* report (2004) at http://files.harc.edu/Projects/CoolHouston/CoolHoustonPlan.pdf.

Figure 5. Albedos of Various Urban Surfaces
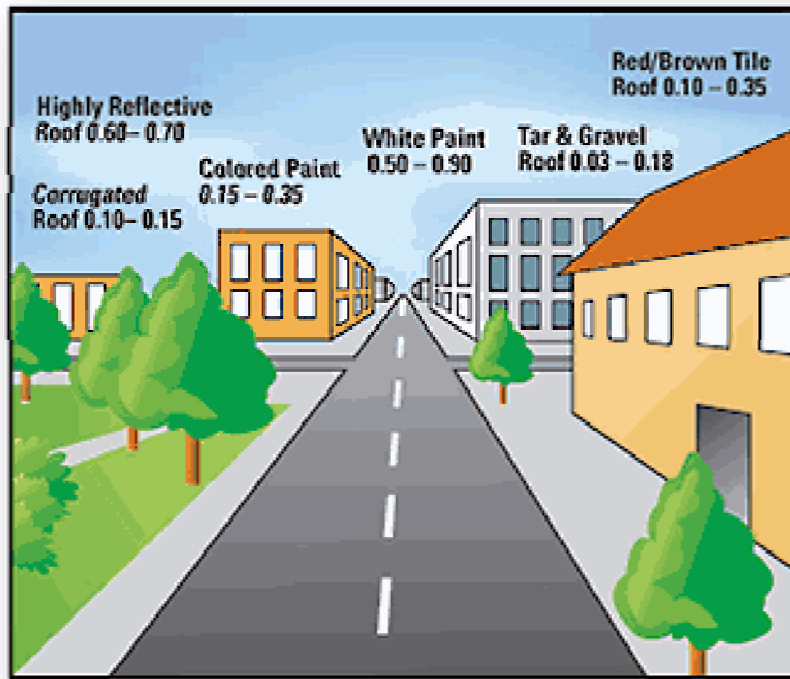
Albedos of various surfaces within the urban fabric. From EPA, 2005a

The Solar Reflectance Index (SRI) measures a material's temperature in the sun. SRI is calculated by multiplying a material's albedo by its emittance. A material's emittance is also measured on a scale from 0 to 1, where 0 signifies a material that does not emit any absorbed heat and 1 indicates that it emits all absorbed heat (EPA, 2005a).

2.1.3   Albedo, SRI and rooftop temperatures

Traditional dark-colored roofing materials, including the black asphalt roofing materials common on New York City buildings, possess low albedos, ranging from .05-.15 (EPA, 2005b). Due to their low albedo, dark-colored roofs can reach temperatures of up to 190°F (87.8°C) during the summer months. Metal-surfaced roofs, including black roofs covered with an aluminum coating, do not have low albedos, but do have lower thermal emittances, which range from 20% to 60% (.2 to .6), as opposed to over 80% (.8) for traditional roofs. For this reason they can also have extremely high summertime temperatures, which range from 140°F (38°C) to 170°F (49°C). Both low albedo and low emittance roofs significantly contribute to the nocturnal heat island effect because they absorb and retain heat during the day, and re-radiate some of this heat at night (EPA, 2005b; Garland, 1997).

2.2   What are cool roofs?

Cool roofs are coated with a high SRI material. They qualify for the EPA's Energy Star label, an EPA standard for energy efficiency, if they contain albedo levels of at least .25 for sloped roofs and .65 for non-sloped roofs (EPA, 2005a). The application of a high-albedo single-ply membrane of elastomeric, polyurethane or acrylic materials is one technique used for flat and low-sloped roofs to become "cool." These membranes can be applied either to newly constructed or preexisting rooftops.

2.2.2 Benefits of cool roofs

Cool roofs directly decrease rooftop surface temperatures, which can potentially lessen the risk of heat-related health impacts and decrease energy used for cooling for tenants in the upper floor of a building. As discussed in Section 3, studies modeling the cumulative effect of widespread application of cool roofs throughout a city project a reduced UHI effect. As described in Section 1, three potential benefits of UHI reduction include lower ozone levels, lower levels of fossil fuel emission from power plants, and fewer negative health impacts.

In addition, a high SRI/albedo roof has a longer lifespan than a traditional roof because cool roofs reflect damaging ultraviolet (UV) rays that traditional roofing materials absorb. The temperature of cool roofs fluctuate less during the course of the day than traditional rooftops. Over time, heat flux can contribute significantly to the deterioration of rooftops. Roof replacement generates significant amounts of waste, energy consumption, transport and landfilling, which lead to high costs for municipalities, replacement costs for building owners, and high levels of environmental pollution (EPA, 2005b).

2.3 Cool pavements as UHI mitigation strategy

Paved surfaces, which can reach temperatures of up to 150°F (65°C), also contribute significantly to the urban heat island effect (Asaeda et al., 1996). Black asphalt has an albedo of .04 at the time of paving and increases to about .12 as it ages over time (Pomerantz et al., 2000b); this low albedo causes it to absorb significant amounts of heat. By reradiating some of this heat during the day and most at night, black asphalt contributes to the UHI effect.

Cool pavements use materials with higher albedos than traditional asphalt and are a viable technology for mitigating the urban heat island (Asaeda et al., 1996). Aseada et al. (1996) demonstrated that the temperature of a light-colored pavement with an albedo of .45 only reached 120°F (49°C), as opposed to 150°F (65°C) for traditional asphalt, although the albedos of cool pavements and black asphalt somewhat converge over time (Levinson and Akbari, 2001)

Permeable paved surfaces also offer the possibility of heat island mitigation. Permeable surfaces enable greater amounts of evaporation, which in turn cools the air. Some experts recommend that urban paved surfaces be porous so that evaporation can be used to cool a city (Asaeda et al., 1996).

Permeable, high albedo pavement also could potentially reduce and filter storm water runoff, and decrease street lighting energy use. Brattebo and Booth (2003) demonstrated that permeable pavement surfaces mitigate storm water runoff, and water infiltrated through these systems contained significantly lower concentrations of copper, zinc and motor oil. Additionally, high albedo pavement improves nighttime visibility, which in turn could reduce street lighting energy use by up to 30 percent (Pomerantz et al., 2000b). Though cool pavement technologies are still being developed, early research shows that high albedo pavements may last up to 10 times longer than black asphalt (Pomerantz et al, 2000a).

2.4 Increased vegetation as UHI mitigation strategy

Vegetation cools cities in three ways. First, strategically located shade trees directly reduce building temperatures by reducing the amount of solar energy that reaches a building's surface (Akbari, 2002). Second, vegetation cools air through evapotranspiration, the process by which plants evaporate water through their leaves. Third, more vegetation means less pavement and more soil; the increased water absorption of soil allows more evaporation to take place, thus cooling the surrounding air. A modeling study conducted for the New York State Energy Research and Development Agency (NYSERDA), discussed below in Section 3, found that street trees "offer the greatest cooling potential per unit area" for surface and near-surface air temperatures in New York City compared to green roofs and high albedo surfaces (Slosberg et al., 2006).

Increased vegetation has other environmental, social, and aesthetic benefits in addition to reducing urban air temperatures. Trees are particularly effective in sequestering large amounts of CO_2 (Nowak, 1993). Vegetation also filters the air by capturing dry deposition, thereby reducing the quantity of near-ground level air pollutants (Taha et al., 1997). Increased vegetation also helps mitigate stormwater runoff by reducing the speed of water flow and enabling water absorption by the underlying soil (NRDC, 2005).

2.4.2   What are green roofs?

Green roofs are living vegetative systems located on rooftops. Green roof systems are currently categorized as either extensive or intensive, depending on the depth of their growing medium. Green roofs are considered "extensive" if they contain two to six inches of soil substrate, enabling the growth of a basic variety of plants, generally sedums. They are considered "intensive" if they contain six or more inches of soil substrate, enabling use of a greater variety of vegetation.

Green roof construction can vary greatly. One of the more common methods, as pictured in Fig.#7, involves a protective layer, drainage layer, filter fabric, specialized growing media, and vegetation over the supporting structure and waterproofing (Green Roof Service LLC, 2007). These components can provide an ideal environment for a living vegetative system and sufficient protection for the roof. Green roofs also are constructed by placing modular trays that contain vegetation on top of a roof's surface. Green roofs can be constructed on new or existing rooftops.

Figure 7. *Functional layers of a typical extensive Green Roof*

① Roof deck, Insulation, Waterproofing ④ Root permeable Filter Layer
② Protection- and Storage Layer ⑤ Extensive Growing Media
③ Drainage- and Capilarity Layer ⑥ Plants, Vegetation
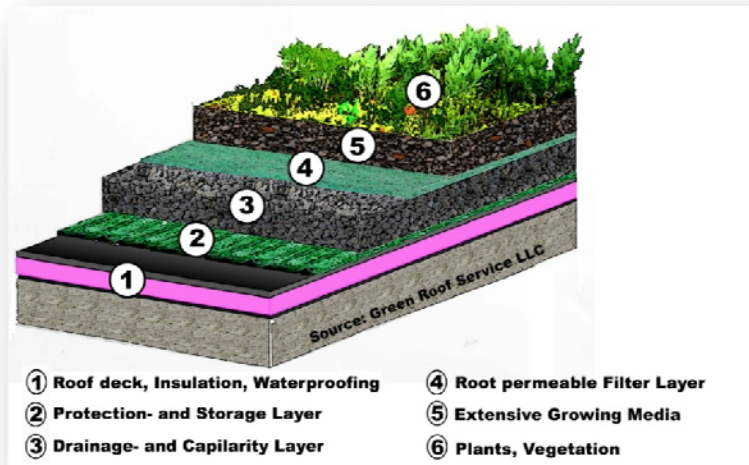
Figure 8. Green Roof Training on Sustainable South Bronx's Smart Roof

Above: Students from Bronx Community Solutions, an alternatives sentencing program, learn how to maintain a green roof from Sustainable South Bronx staff at the Smart Roof Demonstration Project. SSBx's B.E.S.T. (Bronx Environmental Stewardship Training) program provides New York City residents who have barriers to employment, including the formerly incarcerated, with job training, job readiness, and certifications for ecological restoration. Green roof installation and maintenance are important components of the curriculum. To date, there have been eleven sessions, with eighty-seven successful program

graduates. 85% of B.E.S.T.'s graduates are now employed or in college, and 70% are working in the field of environmental stewardship.

2.4.3 Green roofs as UHI mitigation technique and energy reduction strategy

Like cool roofs, green roofs lower the temperature of roof surface membranes; like other forms of vegetation, green roofs cool the air through evapotranspiration and evaporation. However, whereas cool roofs reduce membrane surface temperatures by reflecting solar energy, green roofs reduce membrane surface temperatures due to their shading, insulating, evaporative and evapotranspirative properties (Liu, 2002). Liu of the National Research Council Canada (NRCC) compared the thermal and energy performances of a green roof and a traditional roof, each of which covered areas of 800 square feet on buildings with high Floor Area Ratios (FARs), like large industrial buildings.

Liu (2002) observed that on a 95°F (35°C) day, the green roof's membrane reached 77°F (25°C), and the traditional roof's membrane reached 158ºF (70°C). The study, conducted from the end of November 2000 to the end of September 2001, also demonstrated that the building covered with a green roof used 75% less energy than the building with the uncovered control roof, due to the green roof's improved insulation.

Data from the Penn State University (PSU) Center for Green Roof Research supports these findings: green roof membranes were up to 72°F (40°C) cooler than their traditional counterparts during a hot summer day. The PSU Center observed that in July 2003, the average membrane temperature of a green roof was 34°F (19°C) cooler than traditional roofs during the day and 14°F (8°C) warmer at night. Between the roof insulation and cooling effects, indoor air temperatures of the green roofed buildings were 4°F (2°C) cooler during the day and .5°F (.3°C) warmer at night than traditional roofing (Rosenzweig et al., 2006). Since daytime peak energy demand is greater than nighttime energy demand in the New York metropolitan region, these data suggest that a green roof could help to reduce peak energy usage.

2.4.4 Storm water retention by green roofs

Municipalities across the United States are interested in ways of reducing peak storm water runoff, which can pollute surface water supplies and coastal waterways. Green roofs retain substantially more storm water than traditional roofs during rain events; studies performed at Penn State's Green Roof Research Center and a green roof testing facility in Portland, Oregon, have documented this effect in North American cities. Dr. David Beattie of PSU observed that on average, extensive green roofs retained 80% of rainfall and 74% of peak runoff from June until September of 2003. These results compare with 24% and 26% retention, respectively, on standard reference roofs during the same time period (Rosenzweig et al., 2006).

The City of Portland, Oregon, observed that green roofs captured substantial storm water runoff over a 15-month period. Their study used a ten-story apartment building as a green roof testing facility. Only the west side of the roof was used in the study; this side had a separate drainage system that received water from an area with 66% extensive green roof vegetation and 34%

impervious surface coverage (see Fig. 9, below). The green roof contained five inches of growing substrate (Hutchinson et al., 2003).

Figure 9. Portland Test Green Roof, Hamilton Apartments
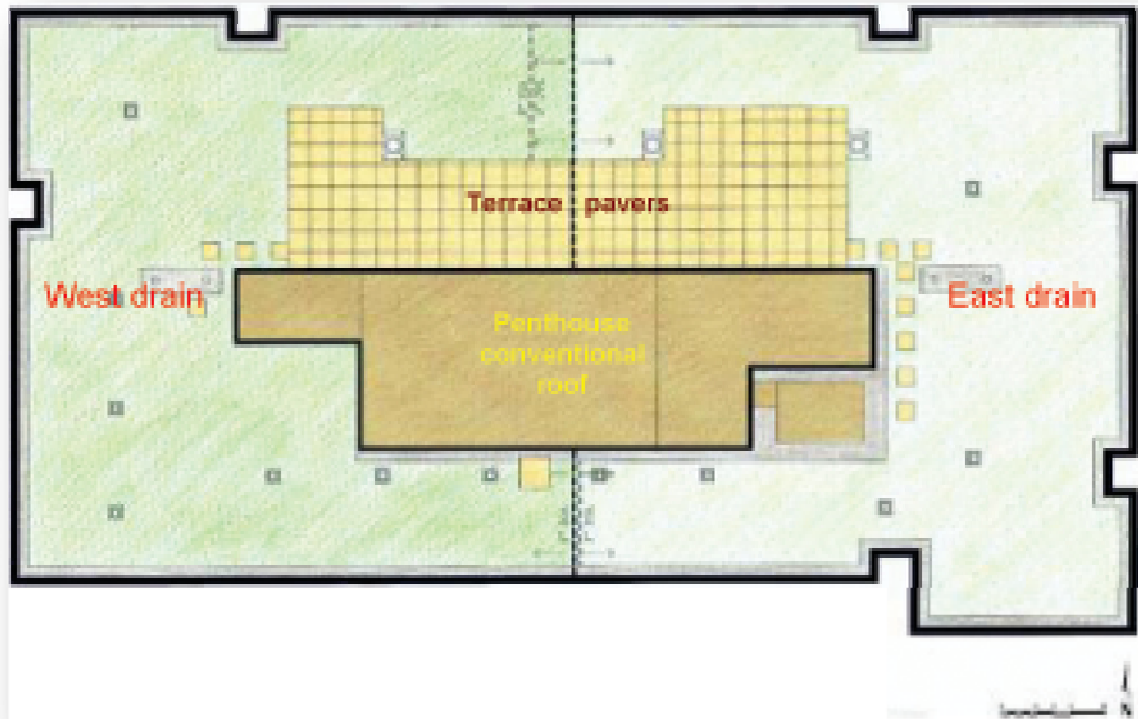
The roof of a 10-story apartment building, which was used as a green roof testing facility by the City of Portland's Bureau of Environmental Services (BES). (Hutchinson et al., 2003) Printed with permission of Portland's BES.

Over the 15-month test period, 69% of rainfall was retained or detained by the west side's green roof, with more rain captured in the final three months than the first three months. The authors suggest that the green roof retained more water during the second year because of the greater maturity of the vegetation. Figure 10 demonstrates that the runoff from a high-intensity, low-volume storm was significantly reduced. Figure 11 demonstrates that green roofs also effectively reduce storm water runoff during a low-intensity, high-volume storm. Generally, storm water retained by a green roof can be released to the environment slowly over time, evaporated, or used by the roof's vegetation.

The peak storm water runoff from a green roof was 1/16 the peak "run-on" rainfall. (Hutchinson et al., 2003.) Printed with permission of Portland's BES.

Figure 11. Storm Water Retention: Low-Intensity, High-Volume Storm, Hamilton West, Portland.
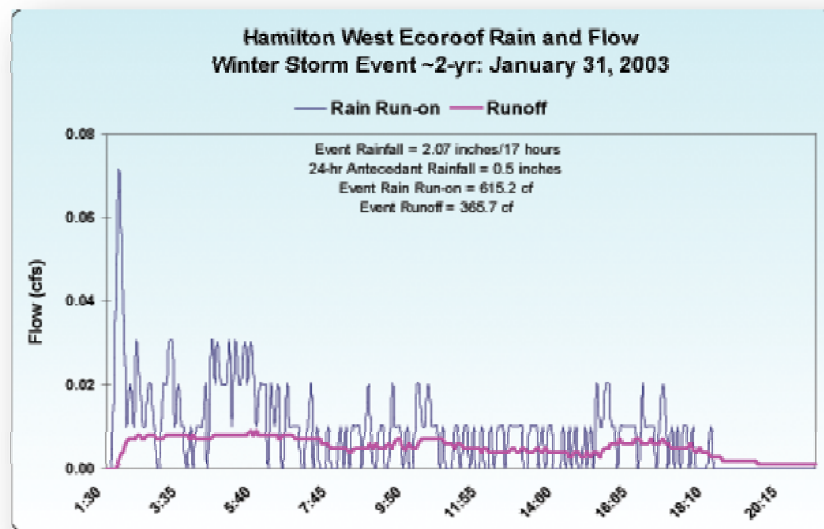
A high percentage of runoff was attenuated from a 24-hour storm. (Hutchinson et al., 2003.) Printed with permission of Portland's BES.

The results of these studies are consistent with others published, despite variations in methodology, location, and time of year. The City of Chicago (MWH, 2004), the City of Vancouver (Graham and Kim, 2003), researchers from North Carolina State University (Moran et al., 2004), and German scientists (e.g. Lieseck, 1998) have investigated storm water retention capacities of green roofs. They demonstrated overall summer retention rates of approximately 65-70%, and average peak storm water retention of about 75-85%.

These impacts are relevant to New York City. 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 rainfalls, resulting in the release of untreated sewage into the city's surrounding water bodies. The city, responsible for keeping its waterways clean under state and federal law, is paying billions of dollars for new infrastructure to reduce combined sewage overflow, or CSO's (NYSDEC, 2004). More research is needed to investigate whether the infrastructural-scale use of green roofs, in conjunction with other ecological infrastructure techniques such as enhanced tree pits and swales, could retain sufficient amounts of peak storm water within a given sewershed and reduce combined sewage overflow. This use of these ecological techniques could potentially curtail the increasing expenses of new construction for CSO abatement in the future.[3]

Following this logic, Tillenger et al. (2006) projected the potential water retention benefits of applying green roofs in the North River Treatment Plant and Newtown Creek sewer sheds. They estimated, assuming the 80% retention observed by Beattie, that applying green roofs to 10% or 50% of the flat rooftops in the North River sewer shed would reduce annual storm water runoff by 2% or 10%, respectively. For the Newtown Creek sewer shed, 10% or 50% application of green roofs would reduce annual runoff by 2% or 9%, respectively (Tillenger et al., 2006).

2.4.5 Other benefits of green roofs

Additionally, because green roofs reduce the temperature fluctuation of a roof's membrane and its exposure to ultraviolet light, they significantly extend a roof's lifespan (Liu, 2002). Extended rooftop lifespan is an economic benefit that accrues to the building owner, while improved air quality and storm water retention are public, rather than private, benefits. As in the case with cool roofs, less frequent replacement of roofing materials would decrease the amount of solid waste produced in cities, and thus decrease the secondary effects of transporting and landfilling the waste. Based on empirical evidence, green roofs are frequently expected to last twice as long as ordinary rooftops—about 40 years. (Sutic, 2003). However, green roof construction companies in the United States currently do not provide a guarantee that the lifespan of a green roof will last longer than a traditional roof's membrane (C. Cheney, personal correspondence, April, 2005).

Green roofs have other benefits. Like other forms of vegetation, they filter the air by capturing particulate matter (dry deposition), and reduce CO_2 levels through photosynthesis (Bass, 2001). Living roofs create urban ecosystems (Brenneisen, 2004). Additionally, prototypes for a new form of urban agriculture have been created on green roofs (Ibid). Green roofs have been incorporated into education curricula (Vujovic, 2004) and they can educate the public by directly connecting the built environment with nature. They are recognized as a form of horticultural therapy in hospital recovery programs (Palmer-Wilson, 2003) and can serve as an amenity for building residents or office workers. Finally, green roofs could improve the overall aesthetic of the urban fabric.

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[3] Adapting a definition by the University of Washington's School of Architecture, ecological infrastructure is applying ecological sciences "and conservation biology to the strategic design of urban infrastructure" and urban form. Ecological infrastructure "looks for ways to structure and guide the flows of organisms, materials, and energy that pass through a city in ways that support the characteristic climate and biodiversity of a region, to preserve the integrity of natural and physical systems, and to protect public health (University of Washington, College of Architecture & Urban Planning)."

3.1 Assessing Potential Strategies for UHI Mitigation

Here we review studies that seek to quantify the impacts of increased surface albedo and vegetation on near-ground air temperatures and air quality in urban areas. Mesoscale meteorological models were used to project the combined effects of changing the albedo of rooftops and pavement. Some studies additionally use atmospheric chemistry models to evaluate the potential impacts of increased urban vegetation on air quality. This section discusses research on the modeled effects of increasing vegetation and surface albedo simultaneously in urban areas. In the following section, research assessing the impacts of green roofs on ambient air temperatures is summarized. Studies analyzing the impacts of increased surface albedo and increased vegetation were performed by the Heat Island Group of Lawrence Berkeley National Laboratory.

3.1.2 Effects of increasing urban albedo

Two studies projected the effects of increasing citywide albedo levels on mitigating the UHI effect in the Los Angeles region of the South Coast Air Basin, or SoCAB.

In the first study of its kind, Taha et al. (1997) measured the effect of increasing albedo surfaces by a "moderate, feasible" .15 and a more ambitious "high" .30 in the SoCAB, simulating changes in near-surface air temperature during a two-day episode in August using a mesoscale meteorological model. The model domain of the Los Angeles basin was comprised of 2,600 grid cells at the scale of 5 x 5 km. Grid cells with certain urban land-use categories, such as residential, commercial, and transportation uses were able to have their albedo increased ('albedo-able'); grid cells comprised of desert, parks or heavy vegetation were not. The study determined the fraction of each grid cell with 'albedo-able' developed land; in those grid cells whose albedo was increased (a total of 392 cells); the average increase in albedo in the moderate and high increase scenarios was 0.07 and 0.13, respectively (ibid, p. 171).

The impacts on near-surface air temperature were significant. By increasing albedo by the "moderate" .15 wherever possible in the study area, afternoon air temperatures (3 p.m.) were decreased by up to 3.6°F (2°C), mostly in the central basin, while temperatures in surrounding areas decreased by about 1.8°F (1°C). Under the high albedo scenario (an increase of .30), temperatures in the central and west basins decreased by up to 4.5°F (2.5°C), while the surrounding areas decreased by an average of 3.6°F (2°C) (Ibid, p.172).

Taha et al. (1997) also simulated changes in ambient ozone concentrations resulting from these changes in albedo. Model simulations with the high and moderate albedo increase scenarios had a net effect of reducing ozone mass in the mixed layer, for a three-day episode in August (ibid, p.169). These simulations took into account changes in air temperature, depth of the mixed layer, wind field, and biogenic hydrocarbon emissions from vegetation that resulted from the albedo increase scenarios.

The high albedo increase (change of .3) led to an afternoon decrease of 640 metric tons in total ozone mass in the mixed layer, a 4.7% decrease (Taha, 1997). The changes in ozone concentrations were not distributed uniformly throughout the SoCAB modeling domain. In some areas ozone

concentrations were reduced by as much as 50 parts per billion (ppb), while in other areas there were ozone increases of up to 20 ppb; "however, the net effect over the entire airshed is a reduction in ozone and a decrease in population-weighted exposure to this pollutant (Ibid, p.1675)." For the moderate albedo increase (.15), a decrease in ozone by up to 240 metric tons in the mixed layer at 3 p.m. in the SoCAB was simulated, equal to a 2% decrease from the base case scenario. Again, a net basin-wide reduction of ozone concentrations and mass was noted.

These simulations indicated that residents would be exposed for less time to ozone over 120 ppb, the National Ambient Air Quality Standard 8-hour exposure exceedance level: a 5% decrease in such exposure with a .15 increase in albedo, and 10% decrease due to a .30 albedo increase (Ibid).

Taha also (1997) evaluated the local consequences of a regional albedo increase by projecting a time series of ozone concentrations. The results varied throughout the region, based on an albedo increase of .30. Ozone concentrations decreased during the day (11 a.m. to 6 p.m.) in certain areas; 3 p.m. reductions were projected in Burbank (25 ppb), the L.A. Civic Center (70 ppb) and Long Beach (35 ppb). Ozone levels increased after 6 p.m., though these increases were smaller than the daytime decreases in these areas. Ozone concentrations did not significantly change in inland areas. Additionally, the modeled concentration of volatile organic compounds decreased throughout the area by 1.5% based on the high albedo increase scenario (Ibid, p.1672).

Biogenic hydrocarbon emissions, ozone precursors emitted from vegetation, also decreased due to the temperature reductions resulting from albedo changes. A moderate increase in albedo (.15) led to reductions of modeled biogenic hydrocarbon emissions by seven metric tons per day (mtpd), equal to a 2% decrease. An albedo increase of .30 resulted in the emission of 13 fewer mtpd, a 3.5% decrease (Ibid).

A recent New York City Department of Design and Construction Report (2007), released by the City in 2008, modeled the energy cost savings from the use of cool roofs on new energy efficient and older inefficient buildings. Their modeling analysis concluded that the while the incremental cost of cool roofs paid for itself on older buildings in "roughly five years (using Con Ed energy rates)," they were not cost-effective on a single-building basis for more efficient new buildings, unless their mitigation of the urban heat island effect was taken into account. When considering the multiple, cumulative benefits of single building energy reduction along with cooling of the City through heat island mitigation, "even the cool roofs on the more efficient new buildings appear to pay for themselves in roughly six years in energy savings alone (ibid, p.23)."

3.1.3   Air quality impacts of increasing urban vegetation

Taha (1996) and Taha et al. (1997) used a mesoscale meteorological model and an air quality model to estimate the impacts of increasing levels of vegetation on near-surface air temperatures and air quality in the Los Angeles basin. An increase in trees by about 10 million new trees in the basin, led to reductions up to 3.6°F (2°C) in ambient air temperature at 3 p.m.; this corresponds to an increase in the estimated average vegetation cover in the SoCab from 16% to 17% (Taha, 1996). An extreme increase of about 20 new million trees in the region produced a reduction of up to 6.3°F (3.5°C) in the west basin and 2.7°F (1.5°C) in surrounding areas, as well as an increase to an estimated 18% average vegetation coverage in the area (Ibid).

This study, although episode-specific, suggested that increasing levels of vegetation throughout the basin would reduce ozone levels only if the new vegetation emitted low levels of biogenic emissions. In the scenarios with low-emitting vegetation, changes in ozone concentrations were geographically heterogeneous over the Los Angeles basin. Although ozone levels decreased overall in most of the region, some areas experienced an ozone increase of up to 20ppb. Planting medium-emitting trees led to increased ozone levels of up to 50ppb in these simulations, and additional levels of high-hydrocarbon emitting trees led to even greater increases in ozone levels (Ibid).

Taha et al. (1997) also estimated the impact of increased vegetation on dry deposition, the process by which gases and particles settle from the atmosphere onto the earth's surface or onto vegetation (EPA, 2005c). The study estimated that 1% of the ozone mass in the mixed layer could be dry deposited due to the moderate vegetation increase scenario. Additionally, simulations indicated that ozone formation could decrease by .6% because NO_2, an ozone precursor, would also be subject to increased dry deposition onto vegetation. Thus, a 1.6% decrease in ozone due to increased vegetation levels was projected by combining these two results. For the same reasons, in the high vegetation scenario, Taha et al. (1997) projected a decrease of 4.5% in ozone levels due to dry deposition; 3.6% from the direct dry deposition of ozone and .9% from dry deposition of NO_2.

Other studies have sought to assess the impact of shade trees on heat island mitigation, energy use and air quality. Akbari (2002) estimated that planting one urban shade tree could reduce CO_2 levels as effectively as three to five forest trees, since urban shade trees can directly reduce energy consumption as well as provide carbon sequestration. For example, he estimates that one well-placed shade tree in Los Angeles could reduce carbon emissions by 18 kg annually (and sequester between 4.5 and 11 kilograms of carbon); and in Baton Rouge, Chicago, and Salt Lake City, each shade tree could potentially reduce annual carbon emissions by an average of 10 to 11 kilograms. In Baton Rouge, it was estimated that planting four shade trees with a crown area of 50 m^2 could reduce carbon combustion by 16,000 tons per year; in Chicago by 41,000 tons, and in Salt Lake City by 9,000 tons. These savings are only based on the direct effects of reducing building temperatures; the indirect effects of reducing electricity use by reducing citywide ambient air temperatures may also be significant if trees were planted on a large, infrastructural scale (such as Mayor Bloomberg's Million Trees NYC initiative). Akbari concluded that if the effect of shade trees on mitigating the urban heat island effect were considered for these cities, reduction of carbon emissions may increase by at least 25%.

3.1.4 Air quality impacts of increasing urban albedo and vegetation

Taha et al. (1997) projected improvements in air quality from simultaneously increasing the SoCAB's albedo and low-emitting vegetation levels. The moderate increase scenario for both vegetation and albedo led to temperature reductions up to 9°F (5°C) in the west basin and 3.6°F (2°C) elsewhere: similar or slightly greater reductions than for the high-albedo scenario previously described. Modeled ozone concentrations from the combined albedo and vegetation change scenario were equal or slightly lower than modeled ozone levels from the high albedo only scenario (Ibid).

This study also estimated the effect of lower citywide temperatures on power plant emissions. Based on projected decreases in energy demand due to the effects on temperature from moderate increases of albedo (.15) and vegetation (an increase of 10 million trees, basin-wide), NO_x levels were reduced by 2.42 tons per day (tpd) at the major Los Angeles Department of Water and Power plant. Reductions from the major Southern Cal Edison power plants were projected, in units of tpd: 4.74 NO_x; .2 PM_{10}; 1.1 CO; and .15 of Reactive Organic Gasses (ROG).

Subsequently, Rosenfeld et al. (1998) assessed the benefits of cool roofs, shade trees, cool pavements and increased vegetation on ozone concentration, smog precursors and NO_x levels in the SoCAB. They simulated altering a 2,500 km^2 surface area comprised of roofs and paved surfaces, or 25% of the city land cover, by an average albedo increase of .3. The study assumed use of light-colored roofs for the 5 million houses in the area, and that 1.8 million of these houses were air conditioned. The study also assumed that 11 million trees with a canopy cross section of 50m^2 were strategically planted throughout the region. Hourly cooling was estimated based on the effects of adding cool roofs and vegetation. They estimated the maximum hourly temperature reduction to be 5.4°F (3°C) at 2 p.m. for the urbanized areas within the Los Angeles basin, approximately 10,000 km^2 of the region.

Based on this maximum 5.4°F (3°C) decrease in ambient air temperature, energy usage was projected to decrease by 1.6 gigawatts (GW), and NO_x by 7 tpd. Subsequently, a 50 times greater *indirect* reduction in NO_x levels was estimated by Rosenfeld et al. (1998) using the following reasoning: a 5.4°F (3°C) reduction in citywide afternoon temperatures would reduce SoCAB ozone concentrations by 10%. A 10% reduction in ozone is equivalent to a 25% reduction in ozone precursors, including NO_x. Thus, the "equivalent" of a 350 tpd reduction in NO_x levels was projected to result from a temperature decrease of 5.4°F (3°C). These projections used base-case temperatures from an August 1988 smog episode.

A study performed in 2000 by Taha et al. projected the potential benefits of increasing both albedo and vegetation levels in Salt Lake City, Baton Rouge, and Sacramento. Using more nuanced projections than in previous studies, they examined the effects of increasing residential roof albedo by .3, commercial roof albedo by .4, road albedo by .25, sidewalk albedo by .2, and parking lot albedo by .25. They assume that each grid cell (residential, commercial, industrial/commercial, mixed urban and developed land, 200m in size) receives an increase of four trees, while each industrial grid cell receives 6 additional trees.

In Salt Lake City, they estimated a reduction of citywide ambient air temperatures by 3.6°F (2°C), with a consequent 3 to 4 ppb reduction in ozone concentrations, a 3.5% decrease from the base case of 95 ppb ozone. In Baton Rouge, these changes were projected to reduce citywide temperatures by 1.4ºF (.8°C); ozone concentrations reduced by 4 to 5 ppb, a 4% reduction in peak ozone concentrations of 113 ppb. For Sacramento, they estimated a 2.2°F (1.2°C) reduction in ambient air temperatures, and a 10 ppb reduction in peak ozone concentrations – an estimated 7% decrease from a peak of 139 ppb (Taha et al., 2000).

3.1.5 Mitigating the heat island effect with green roofs

While the impacts of increasing urban forests and albedo have been analyzed per the discussion above, less is known about the potential effects of the infrastructural-scale use of green roofs on

urban surface and near-surface air temperatures. This section describes some of the research to measure these effects.

In an interdisciplinary study of green roofs in New York City, Rosenzweig et al. (2006) projected the impacts of covering three-quarters of the area of all flat roofs in New York City (NYC), which comprise 11% of the city's surface area, with green roofs. This study used an average rooftop temperature of 113.9°F (45.5°C) from Penn State data for the time period 10 a.m. - 11 a.m. during July 2003. Using August 14, 2002 NYC weather conditions, they estimated that using green roofs on 50% of the city's flat rooftops (with 75% vegetation coverage) could cool the city's surface temperature by up to 1.4°F (0.8°F).

A 2003 study of Toronto's heat island considered how green roofs might decrease urban air temperatures if distributed on a citywide "infrastructural" scale. Bass et al. (2003) studied these effects by using a Mesoscale Community Compressible (MC2) meteorological model that took into account urban geometry and fluxes of movement, heat and moisture, with respect to the city's roofs, walls, streets, asphalt and concrete. This study was based on covering 50% of every city rooftop—which comprised a total of 10% of the surface area of Toronto—with green roofs. Results demonstrated an urban heat island effect ranging from 3.6°F to 5.4°F (2°C - 3°C). The 50% green roof scenario projected citywide temperature reductions ranging from .2ºF to 1.4ºF (.1°C-.8°C) on a June afternoon and evening of 89°F to 93°F (32°C - 34°C).

Bass et al. also estimated the potential cooling effect of irrigating these green roofs as part of a city-wide model irrigation program. The citywide irrigation scenario simulated an increase in soil moisture, particularly in the downtown areas. Soil moisture was approximated at an average of .13 m^3 water per one m^3 of soil for the base case. Bass assumed that "the soil's saturation point was 30% water by volume, and that irrigation of natural areas was more intense the more urban the neighborhood" (Ibid). Irrigating green roofs and other natural areas could increase evaporative and evapotranspirative cooling, reducing citywide temperatures. Results suggested that a city-wide irrigation program, including the irrigation of green roofs, could reduce downtown temperatures by up to 3.6°F (2°C), with green roofs contributing 1.8°F (1°C) to that cooling effect (Ibid).

Another study simulated the impact of using green roofs on buildings in central Tokyo. Two mesoscale meteorological models (MM5) were run to measure the potential effects of constructing enough green roofs such that the city's total evaporative surface area (excluding water surfaces) would increase from 23.6% to 27% and 40% of the city. These numbers were chosen because a city plan aims for central Tokyo to contain 27% evaporative cover for 2015 and eventually 40% in response to a rapidly intensifying UHI. The study used two projections: green roofs were simulated to cover 3.4% and 16.4% of central Tokyo. Model results suggested that increasing the vegetation-covered area in central Tokyo by 3.4% through application of green roofs could reduce its maximum surface area temperature by .2ºF (.1°C), and an increase of 16.4% in central Tokyo's area with green roofs could reduce its temperature by 1ºF (.6°C) (Kinouchi and Yoshitani, 2001).

New York City will need more power plants in the future if peak energy demand increases, without sufficient implementation of energy efficiency techniques in the residential and commercial sector (NYCEPTF, 2004). This section discusses the results of two recent studies that examine how citywide energy demand might be reduced through urban heat island mitigation.

Kerr and Yao of New York City's Office of Sustainable Design, Department of Design and Construction, estimated the potential energy savings in New York City of urban heat island mitigation strategies, including green and cool roofs, higher albedo pavement and increased tree vegetation (Kerr and Yao, 2004). They concluded that a 20-year energy reduction plan would be most effective, as all the roofs and paved surfaces in the city will most likely be replaced at least once during this timeframe. They base their recommendations on the respective payback periods of each mitigation strategy (Ibid).

Kerr and Yao found that for every 1°F (.6°C) increase above 68°F (20°C), citywide energy consumption increased by 3,300 MWh/degree/day. (A linear regression was fit to slightly non-linear data; this correlation is accurate at approximately 75°F (23.9°C) and above, see Figure 4). For cool roofs, the authors extrapolated from an Akbari 1996 study of Los Angeles estimating that cool roofs could reduce New York City's heat island by 1°F (.6°C). They estimated that $105 million dollars per year – $23 million in direct energy savings and $82 million in indirect savings - could be saved if cool roofs were constructed on every roof in New York City at an average additional cost of $.68 per square foot, compared to traditional roofing techniques. Projected savings were based on results from New York City Department of Design and Construction (DDC) energy models of older and newer buildings projecting an averaged annual savings of $.032 per square foot, assuming that 75% of buildings in the city were air-conditioned. Under these assumptions, the cool roof payback period was about six years.

In their analysis, Kerr and Yao estimate that indirect energy savings from citywide cooling are approximately four times greater than direct building-scale energy savings, while Konopacki and Akbari anticipate the opposite relationship – that annual direct energy savings would contribute to 75-85% of heat island-related energy savings, and indirect savings 15-25% in U.S. cities (2002). Konopacki and Akbari's EPA-funded modeling study performed as part of the Lawrence Berkeley National Laboratory's Heat Island Group estimated the following direct and indirect savings: Chicago (82% direct, 18% indirect); Houston (81%, 19%), Sacramento (81%, 19%); Salt Lake City (78%, 22%); Baton Rouge (85%, 15%) (ibid). Further research of the potential for direct energy savings vs. the indirect savings of cool roofs, green roofs, and street trees in New York City is warranted.

For green roofs, Kerr and Yao estimated potential energy savings based on a citywide temperature reduction of 1.2°F (.7°C). This figure is an approximation of Rosenzweig et al.'s (2006) projection of how green roofs on half of citywide roofs could reduce citywide temperatures. Based on these assumptions, the energy savings of greening half of New York City's 944 million square feet of rooftop - at an additional cost of $10 dollars per square foot - would amount to $149.4 million dollars, while the cost would be $4.72 billion dollars. (This is a low figure for the cost of green roof construction; estimates typically start at $15-25 per square foot for building in New York City and

range upwards from there.) The payback period based on these numbers is approximately 31.6 years.

Resurfacing the city's roadways with asphalt containing a white aggregate, taking into account an estimated cost of $59 million, saves energy consumers $57.2 million annually, a payback period of just over one year.

Finally, Kerr and Yao analyzed the costs and benefits of increasing numbers of street trees necessary to reduce the city's temperature by 1.2°F (.7°C), which they assume could be achieved by doubling the number of street trees in the city from 500,000 to 1,000,000. This assumption extrapolates from the conclusions of studies that modeled the potential impact of adding vegetation to the Los Angeles region. The authors assumed that one square foot of a tree's canopy cools the air as effectively as three square feet of green roof. Planting street trees costs an estimated $625 million, with an annual savings of $98.4 million, for a payback period of just over 6 years. However, street tree maintenance costs were not included in this estimate.

Kerr and Yao (2004) concluded that green roofs do not currently merit consideration as an energy reduction strategy based on estimated costs, benefits, and a payback period significantly longer than other UHI mitigation strategies. They note that more research is needed to better understand the full benefits of all heat island strategies, especially in terms of public health, hydrology, roof longevity, and maintenance costs, and that green roofs might be considered more cost-effective if additional public benefits were considered. They conclude that increasing the use of street trees, cool roofs and cool pavements are feasible methods of mitigating NYC's UHI. The estimated payback period for cool roofs is much shorter than green roofs (6 years vs. 31.6 years) based on energy reduction. However potential public benefits of green roofs, such as aesthetic amenities, air quality and stormwater retention are not included in this analysis.

A 2006 modeling study for the New York State Energy Research and Development Authority (NYSERDA) analyzed a set of heat island mitigation strategies for New York City, through a set of scenarios using increased urban forestry, living roofs, and light surfaces to reduce surface and near-surface air temperatures and energy consumption (Slosberg et al., 2006). The investigators modeled New York City's urban heat island during heat wave events using temperature data obtained during three heat waves in the summer of 2002. A goal of the study was to use neighborhood case study sites and different scenarios of mitigation to assess the potential interaction between heat islands, land use categorization, peak electric load and the public health impacts from air pollutants such as ozone.

The NYSERDA investigators found that the use of these three mitigation techniques could reduce surface and near-surface air temperatures in New York City, leading to the reduction of peak electric load during heat waves. The increased planting of street trees produced the greatest cooling potential per unit area and the greatest overall benefits, while the use of light surfaces was found to offer the greatest overall cooling potential, because "64% of New York City's surface area could be lightened, whereas only 17% of the City's surface area could be planted with new street trees" (Slosberg et al., 2006).

The use of higher albedo surfaces offered the most favorable cost/benefit ratio in this analysis. The maximum peak electric demand reductions were estimated as 74.29 MW from planting street trees in 50% of available space citywide; and 200.99 MW through 50% implementation of light surfaces throughout New York City (Ibid).

3.3   A Geographic Information Systems (GIS) analysis of green roof benefits

How can municipalities identify where the development of green roofs might best improve a particular city's environmental quality? The City of Waterloo, in Ontario, Canada sought an answer to this question through use of a Geographic Information Systems (GIS)-based analysis to assess the potential place-based application of green roofs. Waterloo's analysis was designed to evaluate the most cost-effective locations for constructing green roofs on municipal buildings. It was initiated as part of the city's Environmental Strategic Plan, created to improve upon six different environmental planning criteria (see Figures 12-17). Because green roofs satisfy all six criteria, the City of Waterloo undertook a green roof feasibility study (Moyer, 2005).

To evaluate how green roofs could most effectively be distributed throughout the city's municipal buildings, the city mapped the first four of the following six criteria: air quality, storm water runoff, energy efficiency of buildings, green space, environmental awareness, and planning and growth. First, the city evaluated air quality, based on a population-weighted concentration of vehicular traffic, industrial buildings, and air movement. Second, Waterloo evaluated storm water runoff based on which infrastructure would most significantly benefit from reduced volume, and which areas contained the highest concentration of impervious surfaces, did not have a viable water flow alternative, and were most likely to pollute nearby water systems. Third, energy efficiency was evaluated based on the concentration of older buildings, because these buildings were assumed to be the least energy efficient. Finally, green space was evaluated based on the potential to increase its availability throughout the city through green roof construction. The impact of green roofs on improving the view from tall buildings was part of this criterion (Ibid).

The following six maps demonstrate how the city evaluated these criteria individually, and then combined them into an overlay to create their "Overall Green Roof Benefit Maximization Area" (City of Waterloo, 2005).

Figure 12. Area of Greatest Heat Island Intensity, Waterloo, Ontario
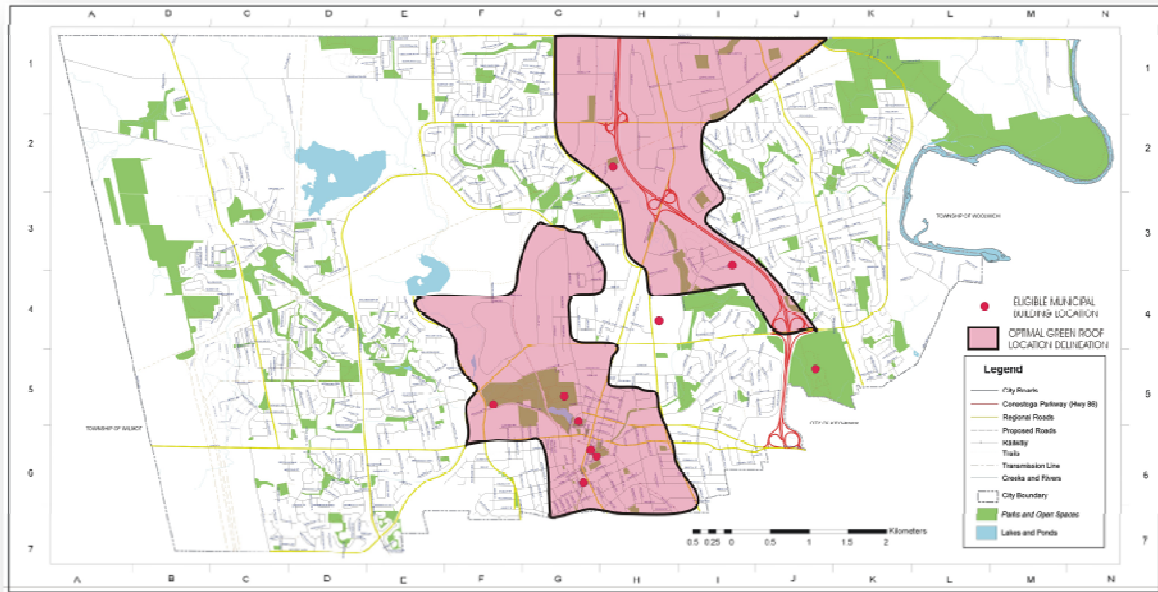
Red zones indicate where the city's heat island intensity is greatest. The authors used thermal imaging as basis for this map. From the City of Waterloo, 2005. All maps printed with permission of the City of Waterloo.

Figure 13. Areas of Worst Air Pollution, Waterloo, Ontario
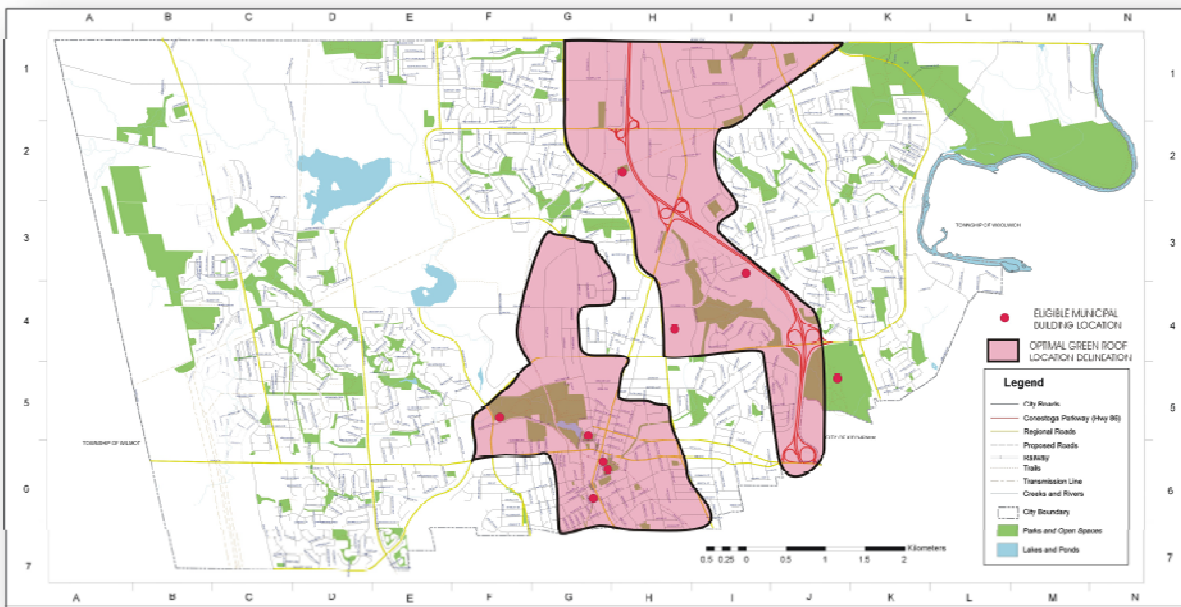
The red zones indicate areas of the city with the worst air quality. The city's heat island was taken into account in this analysis. From the City of Waterloo, 2005.

Figure 14. Storm Water Management Needs, Waterloo, Ontario
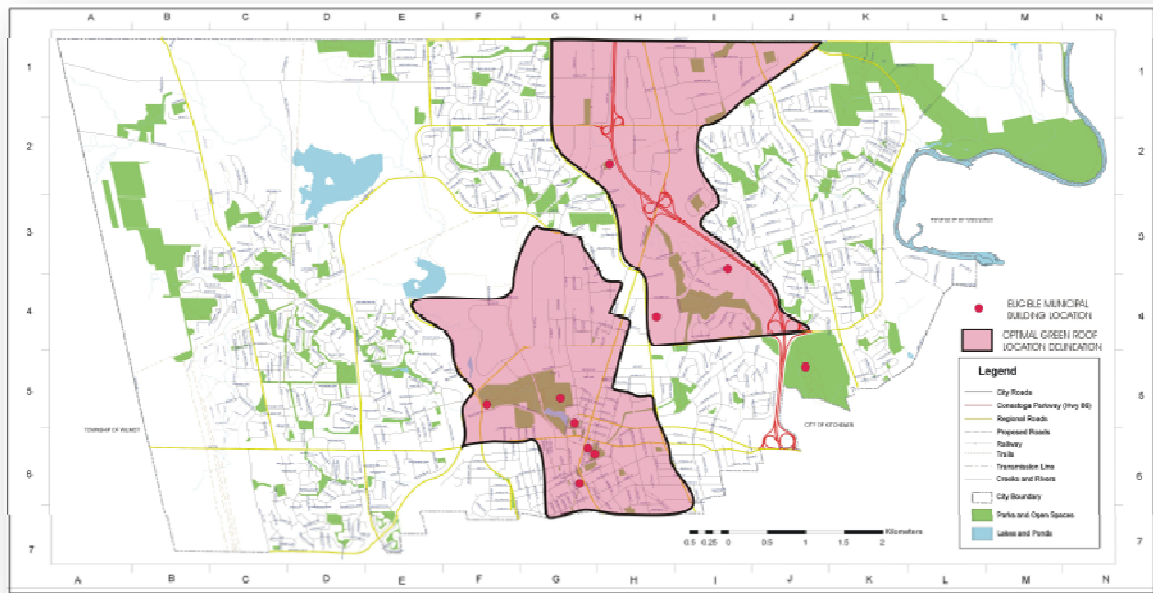
The red zones indicate the drainage areas in greatest need of storm water runoff reduction. A significant correlation exists between areas in need of air quality improvement and storm water runoff reduction. From the City of Waterloo, 2005.

Figure 15. Areas of Greatest Energy Use, Waterloo, Ontario
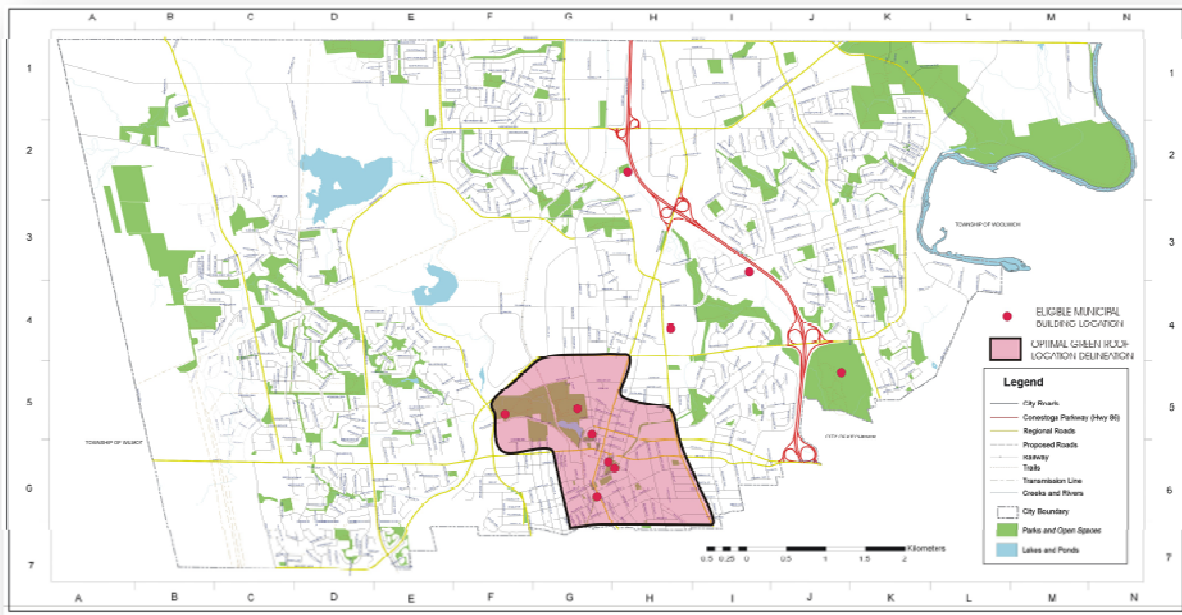
The red zone indicates where green roofs can maximally increase open space. From the City of Waterloo, 2005.

Figure 16. Green Space Priority, Waterloo, Ontario
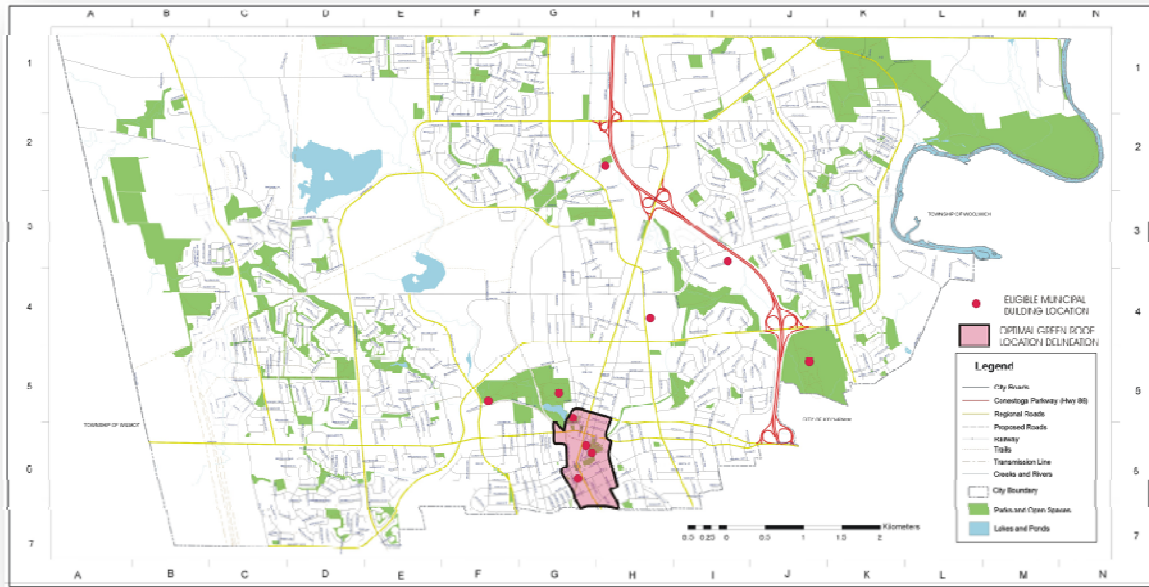
The red zone indicates where green space can be increased via green roof construction. From the City of Waterloo, 2005.

Figure 17. Overlay of Green Roof Benefits, Waterloo, Ontario
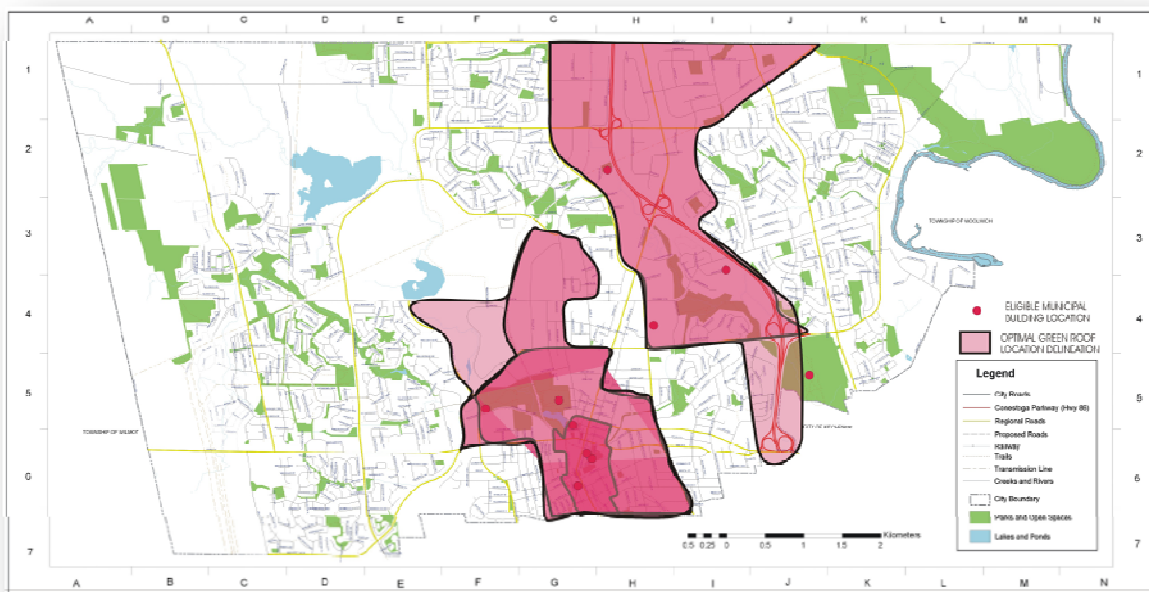
"Overall Green Roof Benefit Maximization Area" (City of Waterloo, 2005).
The five previous maps were overlaid to demonstrate the green roof maximization areas (above). The darker the shade of red, the greater the benefit of constructing green roofs.

Interest in the application of green roofs as 'ecological infrastructure' has led to a few efforts to assess their costs and benefits if applied at a widespread scale in cities. This section briefly discusses some issues related to cost-benefit analysis for green roofs in American cities, and one study on New York City (NYC) in particular. As mentioned above, the construction cost of cool roofs is low relative to the installation of green roofs, and cool roofs are considered cost-effective for use in NYC.

Efforts to quantify and monetize the full costs and benefits of urban green roofs have encountered two key problems. First, it has been difficult to fully assess the potential value of the public benefits of widespread construction of green roofs. Public support for green roof subsidies or incentives in cities like New York and Chicago are based on their potential environmental benefits, such as cleaner air, aesthetic appeal and detained stormwater. However, it has proven difficult to quantify and monetize potentially significant public benefits such as improved air quality and public health and reduced stormwater volume for several reasons. Too little data currently exists to determine these lifecycle costs and benefits of green roofs with greater precision.

Second, the costs of green roof components and installation would be likely to change as the industry expands. Green roof installation has been a growth industry in northern Europe and a significant green roof industry emerged in Germany over the last two decades. While in its infancy in the United States, the green roof industry nets over $780 million dollars per year in Germany (Boyle, 2005). If a national or regional market emerged at this scale, business competition and investment in materials may well lead to decreases in the currently high costs of green roof installation, which start at roughly double the cost of a standard, non-green roof.

A few cost-benefit analyses have made preliminary estimates of the costs and benefits of heat island mitigation strategies in NYC and other cities, despite the difficulty in monetizing and estimating public benefits. Roy F. Weston, Inc. performed a study in 1999 to evaluate the potential energy savings of constructing a green roof on every roof in Chicago, which amounts to 30% of the city's surface area. They estimated that this could reduce annual energy costs by $100 million and peak energy demand by 720 megawatts (Rosenzweig et al 2006). This study did not specify whether indirect energy savings from heat island mitigation were included.

A study performed by Kenneth Acks (2006) of the Cost Benefit Group analyzed the public and private costs and benefits from the use of green roofs both at a large (infrastructural) scale in NYC and for individual private buildings (Rosenzweig et al., 2006). Costs and benefits of green roof implementation were stratified into low, medium, and high scenarios of green roof performance. Model parameters such as installation and maintenance costs, service life, and energy used for cooling were estimated by extrapolating from the best available studies, although NYC-specific data is lacking.

The study provided cost-benefit estimates for two scenarios: private installation of a green roof on 75% of an average flat roof in New York City (an estimated 1,798 square feet of green roof); and green roofs built throughout the City, with 50% of the City's flat roofs greened, yielding 4.2% of the land area in NYC covered with living roof systems.

At an infrastructural scale, such as 50% of flat rooftops converted in this scenario, both cool and green roofs entail the creation of a public good on private and public property. Private, building-level costs for using green roofs include installation, related engineering and architectural expenses, and green roof maintenance, and would accrue to building owners or residents. Benefits to private building owners include reduced energy use for cooling; increased roof lifespan, sound insulation, aesthetic value, and possibly, food production.

A key feature of the use of green roofs at an infrastructural scale are the potential public, community-level or city-wide benefits, including: reduced expenditures due to stormwater runoff; reduced urban heat island effect; improved air quality due to reduction in particulates, NO_x, ozone, SO_2, CO_2 and CO; improved public health due to decreased air pollution; aesthetic benefits; and increased employment due to job creation. A cost for public administration of a city program to support green roofs was assumed.

The study further divided the analysis into two tiers of estimated costs and benefits. Tier I included major benefits and costs for green roof implementation, such as heat island and stormwater runoff reduction. Tier II included additional estimated private and public benefits in sound reduction, public health impacts, greenhouse gas reduction and aesthetic amenity.

The study's preliminary estimates of environmental benefits include:

Energy/heat island: To calculate the medium-range of direct energy benefits, Acks assumed a 15% reduction in the cost of cooling, estimating a savings of $.16 per square foot. For energy reduction benefits due to indirect heat island mitigation, an additional 5% reduction in energy demand for cooling was estimated if citywide temperatures were decreased by .8°F (.4°C).

Hydrology: Acks estimated that green roofs could capture either 20% (low scenario), 50% (medium scenario), or 80% (high scenario) of stormwater. The low, medium, and high scenarios projected savings of .6%, 1.9% and 3.4%, respectively, of the city's $180 million overall wastewater treatment capital expenditures. The study assumed that overall operating costs could be reduced by 10% of capital expenditures, or $18 million.

Air pollution and greenhouse gas reduction: Particulate reduction was estimated at .44 pounds per square meter of green roof, based on the ability of grass to filter air. Decreases in other air pollutants were assumed to be 10-30% of the reduction in airborne particulates. Health benefits were based on EPA estimates of what a person is willing to pay for a longer and healthier life.

Lifespan of roof: Green roof lifespan was estimated at 20, 40, and 60 years for the low, medium, and high performance scenarios, respectively. Installation costs of green roofs in the medium scenario were estimated at $18 per square foot.

In conclusion, this study suggests that the city should consider green roof infrastructure a cost-effective UHI mitigation strategy when all potential public benefits are considered. The medium performance scenario for green roofs as ecological infrastructure yielded a positive cost-benefit ratio when all the estimated public and private benefits were included in the model. This includes the most detailed preliminary estimates of a green roof cost-benefit analysis for New York City to date. However, this study did not estimate all potential impacts, such as reduced power plant emissions from directly and indirectly reduced energy demand and changes in ambient ozone concentrations from heat island mitigation.

3.4.2   Public and private costs and benefits of UHI mitigation techniques

A key strategy for public policy is to subsidize the private costs of green roof development, in order to maximize their implementation and public benefits. The following chart illustrates the relevant public and private costs and benefits of cool and green roofs, in the context of urban heat island mitigation. The cost of their construction on private buildings would be paid for by private owners, except when public incentives, such as tax abatements or direct subsidies, are provided.

Figure 18. Summary of Private and Public Costs and Benefits of Green Roofs (GR) and Cool Roofs (CR) on Privately Owned Buildings in New York City

Direct Benefits from reducing building temperatures	Private	Public
Energy Savings	Yes	No
Reduced heat-related illnesses and mortalities	Yes	No
Reduced Stress on Grid & other Energy Transmission Systems	No	Yes
Reduced Greenhouse Gas Emissions	No	Yes
Filtered Air Pollution	No	Yes
Public Health Benefits of Improved Air Quality	No	Yes

Indirect Benefits from reducing citywide temperatures (UHI Mitigation)	Private	Public
Further Energy Savings at building scale (Due to Lower Ambient Air Temperatures)	Yes	No
Reduced Stress on Grid & other Energy Transmission Systems, reducing maintenance and capital costs	No	Yes
Prevented Power Plant Construction/Re-powering	No	Yes
Public Health Benefits of Reduced Ozone Concentrations	No	Yes
Reduced Greenhouse Gas Emissions	No	Yes

Additional Benefits	Private	Public
Roof Protection	Yes	No
Building Amenity	Yes	No
Educational Resource	Yes (GR more than cool roofs)	Yes, if on publicly accessible building
Aesthetic Value (Potential addition of open space)	Yes	Yes
Urban Agriculture	Yes	No
Reduced Water Treatment/CSO	No	Yes
Associated Prevention of Water Treatment Infrastructure Construction/Expansion	No	Yes
Associated Improvement of Estuary Water Quality	No	Yes
Biodiversity	No	Yes

Costs	Private	Public
Building Structural/Engineering Work	Yes	No
Installation/Design	Yes	Yes: $4.50/s.f. GR tax abatement for certain buildings in NYC up to $100,000
Maintenance	Yes	No

Note: Benefits of Only Green Roofs shaded in green
Benefits of Both Green Roofs and Cool Roofs in black
Adapted by R. Crauderueff from G. Hockert (2004).

4.1 Conclusion and Recommendations

Our review of the literature, though not exhaustive, provides strong evidence that urban heat island mitigation strategies such as cool roofs, living green roofs and urban vegetation can play a role in reducing urban electricity demand, improving air quality, cooling the urban environment and diminishing stormwater runoff pollution. Though these roof projects are just a small part of emerging green building technologies, they can help to offset the carbon footprint of existing and new buildings, while providing additional value and environmental improvement.

We conclude with three recommendations for New York City with regards to the two main approaches discussed in this report, cool and green roofs: the city must support further research with community-based organizations for effective place and neighborhood-based heat island mitigation strategies; the city must continue to expand efforts to address summertime heat as a public health issue; and the city must develop and phase-in additional mechanisms and policies to support climate adaptive strategies in the built environment, and ensure they are adopted in major development projects.

(1) Place-based analysis of the potential use of ecological infrastructure and urban heat island mitigation could create a more effective plan for city neighborhoods:

Although the capacity of cool and green roofs to reduce surface temperatures on roofs and green roofs to retain and delay runoff are well-documented, research is needed on a local neighborhood scale to assess where the use of these approaches may be most advantageous, and to what extent their use might impact urban environmental problems.

Community and infrastructure needs vary throughout the city. By partnering with community-based and environmental organizations, business, private real estate organizations, and other relevant stakeholders in the evaluation, planning, and implementation stages, the city could increase its capacity to identify the appropriate scale and mix of heat island mitigation strategies and to facilitate their implementation. Research to quantify potential stormwater and energy benefits of heat island mitigation strategies in neighborhoods, and to coordinate green building strategies with housing affordability strategies, should be a priority.

The GIS-based analysis performed by the City of Waterloo, Canada, described above provides a good model for New York City's evaluation. It analyzes the spatial distribution of air quality impacts, heat island intensity, stormwater drainage and open space availability to determine places where the use of green roofs might hold the greatest benefit. We also recommend that spatial analyses performed by the City include environmental justice criteria developed in partnership with impacted environmental justice communities, and an assessment of the non-governmental organizational partners that may collaborate with the City in implementation of PLaNYC objectives.

As our brief discussion on green roof cost-benefit analysis indicated, the difficulty in estimating their public externalities highlights the current shortcomings of cost-benefit analysis as a public policy decision-making tool. The full range of public benefits of all heat island mitigation techniques

should be considered to the greatest extent possible while planning to develop and implement a heat island strategy.

As the green roof industry in Germany has demonstrated, there is significant economic development and jobs creation potential in environmental businesses. Research on the best ways to leverage public support to encourage the creation of jobs in environmental industries that create pathways out of poverty should be prioritized.

(2) Climate-health impacts:

Summertime heat is a public health stressor. In addition to operating public cooling stations and informing the public about the risk of extreme summertime temperatures, the city may consider policies to support modifications in the built environment that aim to reduce the impact of extreme summertime heat on senior citizens in the low-income residential neighborhoods most likely to be at risk. A good model is the Philadelphia's Energy Coordinating Agency's (ECA) Cool Homes Program, which targets the homes of vulnerable populations for use of cool roofs, improved ventilation and insulation. These strategies, along with supportive housing and neighborhood heat health alert systems, may lower the risk of heat related health impacts for the most vulnerable urban residents, while not increasing the peak electrical demand associated with air conditioning use on hot summer days.

(3) All levels of government can play a role in providing incentives for climate adaptive strategies in the built environment:

New York City has taken several meaningful steps to provide incentives for the implementation of green and cool roofs, to encourage market transformation and save municipal dollars. Heat island mitigation strategies have been incorporated into the Mayor's PlaNYC 2030 long-term strategic plan. The city's new building code, effective July 2008, was amended to enable green roofs through inclusion in the code and to require all flat or low-sloped roofs to be covered by a white or Energy Star reflective roofs for at least 75% of the area of the roof or setback surface, along with other green building provisions.

A green roof incentive was also incorporated into PLaNYC. The City supported a one-year property tax credit of $4.50 per square foot of roof area converted to green roof, when at least 50% of the available roof is greened. SSBx advocated, along with partners in the Storm Water Infrastructure Matters (S.W.I.M.) coalition, for passage through the New York State legislature of the bill that enabled this tax abatement to take effect in June 2008.

According to S.W.I.M., this incentive can potentially cover approximately 25% of the costs associated with the materials, labor, installation and design of a green roof. The City will need to develop a transparent and expeditious process to effectively encourage private building owners and developers to use the incentive. Plans should be further developed and dates confirmed to phase these incentives into place and to evaluate their effect, on both the environment and the creation of green-collar jobs, to support the greening and cooling of New York City's neighborhoods.

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