Rising Temperatures and Expanding Megacities:

Improving Air Quality in Mexico City through Urban Heat Island Mitigation

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Abstract

Mexico City exists as a cityspace pushed and pulled in multiple directions. Different scales and levels of spatial reference and planning have come together to produce a dynamic and contradictory place united by the identity of Mexico City. Unfortunately, the city faces a regional environmental dilemma stemming from its chronic air pollution problem. Many steps have been taken to reduce air pollution in the city and this study examines an additional air quality improvement strategy that has been implemented in other megacities.

Singapore and Tokyo have supplemented their air pollution reduction programs with Urban Heat Island (UHI) mitigation plans. Across the globe, cities experience a phenomenon called the UHI effect where urban areas are several degrees warmer than neighboring suburban or rural areas. A cycle of consuming more energy for cooling purposes adds to greenhouse gas production from the additional power generation and then feeds back to the system with yet higher temperatures in the city. In addition, higher ambient temperatures help speed the formation of smog. This study examines what Tokyo and Singapore have done in terms of an UHI mitigation plan, analyzes what can be done to reduce the UHI effects in Mexico City to improve air quality and quantifies the effects of potential physical changes. Modest surface changes are modeled and predicted to reduce average temperature by more than a full Fahrenheit degree. A decrease in surface temperature can slow the formation of smog and can help mitigate the impacts of the Urban Heat Island effect.

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Introduction

Mexico City faces a regional environmental dilemma stemming from its chronic air pollution problem. Daily pollution levels often exceed air quality standards and it is imperative to implement effective pollution control strategies. This study presents the Urban Heat Island (UHI) mitigation framework as an air quality improvement strategy to be used in concert with current air quality improvement work in Mexico City. This strategy exists within the various types urban planning growth strategies such as transit-oriented growth or New Urbanism. Utilizing the UHI mitigation framework in Mexico City provides a unique opportunity to bring together a more holistic perspective on how urban form and design can be integrated with ecological principles and technology to plan cities in a more sustainable way.

Most of the air pollution control work in Mexico City has focused on transportation-related strategies. Across the United States and beyond, though, efforts to step beyond these traditional air pollution controls have appeared. Cities as diverse as Austin, Texas, Toronto, Ontario, Sacramento, California, Tokyo, Japan and Singapore are all attempting to improve air quality by adding Urban Heat Island (UHI) mitigation strategies to their list of pollution control strategies.

The relevance of the UHI framework to Mexico City and estimates of the potential effect of UHI mitigation in Mexico City will be presented in this study. Specifically, Chapter One establishes links between land use and urbanization and their relationship to air quality. Chapter Two describes the UHI concept, what drives the phenomenon, previous research on UHIs and UHI mitigation and what strategies can help reduce the UHI effect. Chapter Three examines the cases of Tokyo and Singapore and how these two cities justify their UHI plan and how they keep the public interested in this topic. Chapter Four describes a potential UHI mitigation scenario in Mexico City and estimates the benefits of surface changes and Chapter Five examines the status of UHI work in Mexico City and some considerations for planning a UHI mitigation strategy for the City.

Research Methodology

In an attempt to define potential benefits of UHI mitigation approach in Mexico City, this study combines qualitative and quantitative analyses. Case studies of Tokyo and Singapore provide the setting for the qualitative analysis of the situation. Key features of their UHI mitigation programs are highlighted, including: motivations, key players, details of the implementation plan, results of city-specific studies and public perception of the UHI mitigation work. The quantitative analysis uses satellite imagery to find a spatial relationship between temperature and land use information.

This framework of analysis allows for an integrated approach to determining the usefulness of UHI mitigation for air quality improvement. The quantitative portion measures the potential physical impact surface changes can make to the city. Case study analysis helps define the relevant institutional and community issues that determine if UHI mitigation could actually be brought to Mexico City.

Relevance to Urban Planning

Mexico City faces the same issues large cities in the developing world face, which include, but are not limited to water supply and wastewater issues, urban sprawl and severe air quality problems. Studying cities facing these urbanization issues is especially timely considering urban population growth in developing countries is predicted to expand faster than rural populations in the next 30 years. In Mexico City, this growth is characterized by expansion along the city periphery and a decline in population in the downtown area.[1] This translates into forest cover loss in the ecological zones of the city and inefficient use of existing infrastructure in the developed city center.

With limited budgets for infrastructure projects and ecological restrictions as to where conserved and native species can exist, this growth in Mexico City is insensitive to the long-range needs of a city's residents. Sustainable cities integrate urban design, energy efficiency and awareness of ecological principles into the planning of a city. UHI mitigation strategies to improve air quality lie at this intersection of science, technology and urban planning.

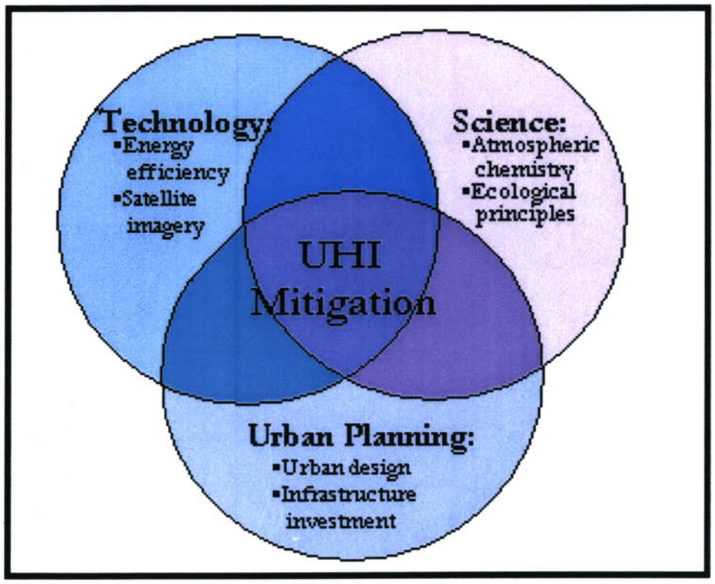

Figure 1: Intersection of technology, science and urban planning

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[1] Atrian, 2003.

Chapter One: Linking Land Use, Air Quality and Urbanization

Growth in urbanization manifests itself by a reduction in green space. The quality of urban air is significantly being marginalized as cities spread out over an area.[2] Transportation networks grow in response to this laterally-focused growth: in Mexico City, travel times, and thus emissions, are increased as residents move out to the periphery. With decreasing amounts of green space, there is less vegetation to sequester the increasing amount of carbon and particulate matter in the air. Later in this study, it will be demonstrated that the amount of green space affects temperature and influences the Urban Heat Island effect.

Land Use

Green space areas are quickly disappearing and changing into residential and commercial areas. This methodical transformation is attributed to the conversion of conserved forestlands into informal settlements, the movement of wealthier citizens from city centers to more spacious periphery areas and pressures of economic growth pushing real estate development. The World Health Organization (WHO) recommends cities have 9 m^2 of green open space per dweller. Mexico City falls well below this standard with 5 m^2 of green space per city dweller.[3] The amount of green space in the city will not rise to the WHO standard unless there is a concerted effort to maintain and increase the green space in the city. In the southern periphery of Mexico City there is a vast area conserved for ecological purposes. This area is so large and so heavily forested that informal settlements that appear can go unnoticed for long periods of time.

Air Quality in Mexico City

Mexico City has one of the worse cases of atmospheric pollution in the world. Daily pollution levels regularly exceed national air quality standards. Figure 1-1 illustrates the percentage of days a year that pollutant standards were exceeded from 1988 to 2000. Out of the six problematic pollutants in Mexico City, ozone is the worst offender with violations 80% of the days.

Ozone is a major compound of smog, which is the most visible manifestation of poor air quality. Surface ozone comes about from a reaction between volatile organic compounds (VOCs) and NO_x in the presence of sunlight.[4] Ozone concentrations increase to levels harmful to humans in hot and sunny weather conditions with little or no wind.

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[2] Molina, 2002.

[3] Atrian, 2003.

[4] http://www.epa.gov/region01/eco/dailyozone/oz_prob.html.

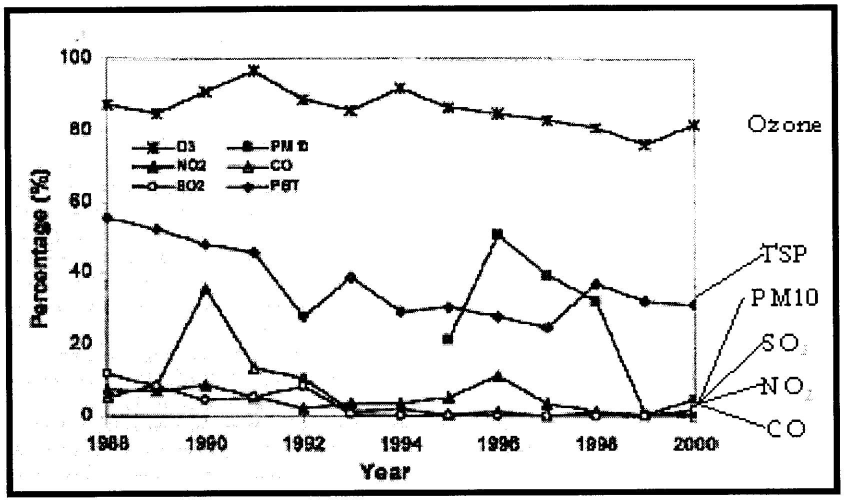

Figure 1-1: Percentage of days a year ozone, nitrogen oxides, sulfur dioxide, particulate matter (10μm), carbon monoxide and total suspended particles standards were exceeded. Source: Molina, 39; based on INE, 2000b, Almanaque de Datos y Tendencias de la Calidad del Aire en Ciudades Mexicanas.

The Mexico City air pollution issue was acknowledged in 1970s and addressed in policies in the 1980s and 1990s. Despite mitigation efforts, the air quality problem has persisted. Much of the city's air pollution comes from transportation-related sources. Almost all of the CO, 80% of NO_x, 40% of VOCs, 20% of SO_2, and 35% of PM10 come from transportation-related sources.[5] Many of the Mexico City pollution control strategies have focused on transportation-related policies, but mitigation efforts have also looked at improving fuel quality and replacing fuel oil power generation with natural gas power generation. See Appendix A for an abbreviated list of air pollution reduction measures.

Despite the fact that much of the Mexico City pollution comes from transportation-related sources, it would be remiss to simply focus on transportation-related pollution sources. It is necessary to take a step back and examine the fundamentals of urban living and assess what seemingly small surface changes can also be taken to manage air quality.

The Physical Layout of Mexico City Contributes to Air Pollution

Mexico City lies in a high altitude (2200 meters above sea level) basin almost completely surrounded by hills and mountains (including dormant/active volcanoes) with an opening to the north. This chain of mountains around the city traps pollutants and concentrates the pollutant level inside the Mexico City basin. The altitude of the city exacerbates the situation. At higher levels, there is less oxygen in the air compared to areas at sea level. The public health problem is multiplied

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[5] Molina, 2002.

because residents not only have to intake polluted air, but they must inhale more of it to compensate for the high elevation.

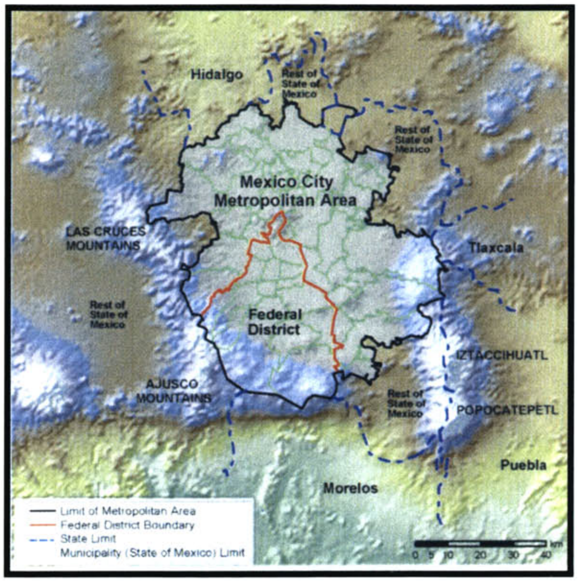

Figure 1-2: Topographic map of Mexico City (Source: Molina, 2002).

Another interesting consequence of Mexico City's physical layout is the eastern part of the city is subject to severe droughts and floods. In the rainy season (June to September) the city experiences heavy rainfall. The natural drainage pattern has been reversed to accommodate urban development and has led to massive floods throughout the summer. The rest of the year, these areas face water shortages.

Urbanization

For the purposes of this study, urbanization is viewed as the conversion of land to built-up space. Built-up space includes buildings, roads, and other developed areas associated with urban regions. Urbanization is associated with the loss of green cover. In Mexico City, urbanization is happening at multiple levels, simultaneously. Wealthier citizens have been abandoning their homes in the city center and moving to areas in the periphery with more living space. At the same time, informal settlements are appearing in the less desirable periphery areas. Most of these settlements are illegal, but eventually these areas are legitimized when their political power becomes strong enough and the government provides city services and infrastructure.

Urban population growth in developing countries is predicted to expand faster than rural populations. According to the United Nations' World Urbanization Prospects, 2001 Revision Report, "the proportion of urban dwellers rose to 47 per cent by 2000 and is projected to attain 60 per cent by 2030." Megacities in the developing world face several problems stemming from this increased urbanization including water and air pollution. In the face of this increasing urbanization, it is imperative to consider these trends and plan cities accordingly.

In Mexico City, the urbanized area increased from 118 km^2 in 1950 to 1500 km^2 by 1995.[6] Figure 1-3 illustrates the urbanization increase experienced in Mexico City during the 20th century.

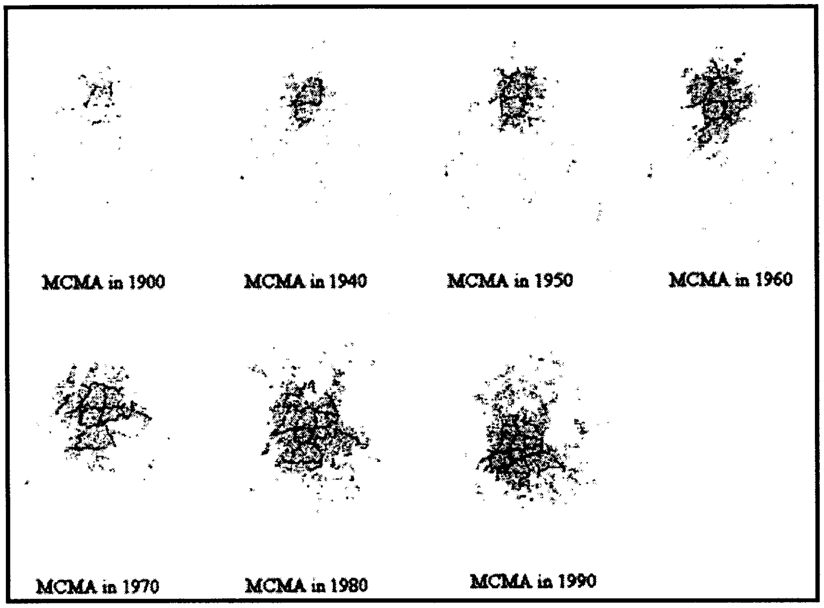

Figure 1-3: Increasing urbanization in Mexico City (Source: Gilat, 2002).

Mexico City's increase in urbanization area was accompanied by an increase in average annual temperature. From 1900 to 2000, average annual temperature increased from 58.6°F in 1900 to 62.2°F in 2000.[7] This temperature trend will be further explored in Chapter Four.

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[6] Molina, 2002.

[7] Jauregui, 2003.

Chapter Two: Nexus of Temperature, Air Quality and Land Use: The Urban Heat Island Concept

Examining the air pollution issue through the lens of the UHI framework helps describe the complex interactions between land use, temperature and air quality. The United States Environmental Protection Agency (US EPA) recognizes temperature as a contributor to smog, on the same level as NO_x.[8] It is therefore important to consider what factors influence temperature and how to mitigate its impacts. This section will explore the mechanism of the UHI cycle, previous research on the temperature, land use, air quality connection and the relevance of this relationship to urban planning.

Urban Heat Island Cycle

Urban environments and their rural surroundings differ in climate types. In urban areas, buildings and paved surfaces have gradually replaced pre-existing natural landscapes. This conversion altered albedo values, which determine the amount of solar energy absorbed into a material. As surfaces change from green space to buildings and paved areas, more solar energy is absorbed resulting in increased temperatures. UHIs appear where there is a high concentration of low albedo surfaces.

Influence of Albedo:

Before widespread use of mechanized air conditioning, residents planted shade trees and whitewashed homes to help cool indoor environments. The prominence of these practices has decreased and this physical change has helped contribute to a decrease in albedo.

Albedo is a measure of the amount of solar energy reflected by the surface. Figure 2-2a gives sample albedo values for a variety of urban surfaces. A low albedo value, such as tar and gravel, implies higher surface temperatures since less energy is reflected and more short-wave radiation is absorbed. As surfaces throughout an entire community or city change to materials with lower albedos values, surfaces become hotter and overall ambient air temperature increases. This phenomenon can raise air temperature in a city by 2-8°F. Figure 2-2b illustrates the temperature difference as land cover type changes. The warmest land use type is the downtown area, where there is normally little green space and where black asphalt roads and black rooftops

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[8] Gadja and VanGeem, 2001.

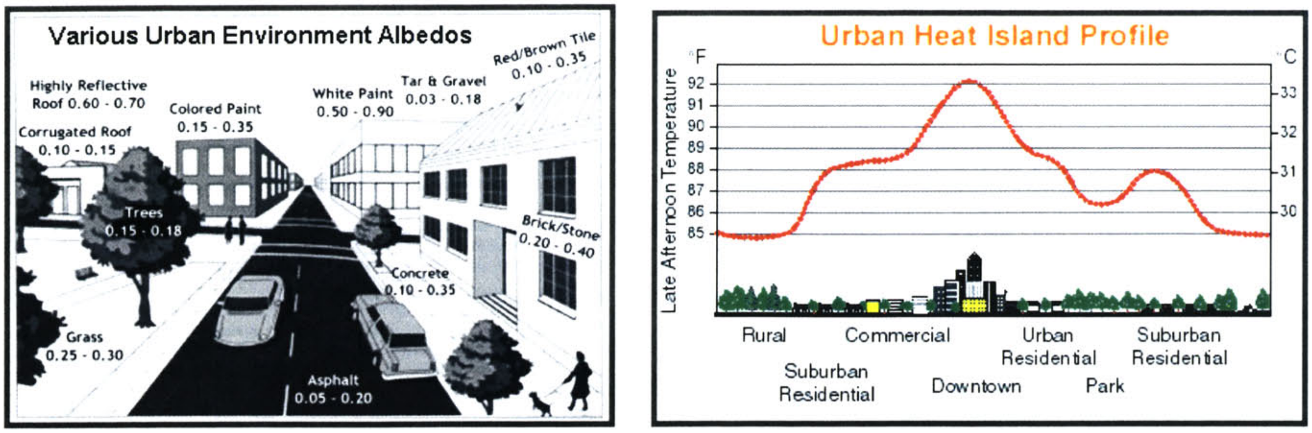

Figure 2-2a and b: a) Various urban environment albedos b) Urban Heat Island profile: temperature of different land cover types (Source: http://www.ghcc.msfc.nasa.gov/urban/uan_heat_island.html).

dominate. Urban residential areas are cooler because, generally, more green space is interspersed between housing units. The coolest urban land use is parkland. Parks are cooler because trees lower ambient temperature through a process called evapotranspiration.

> "Evapotranspiration is the process through which intercepted radiation is utilized by plants, soils, and water bodies to convert water to water vapor. The use of this energy in the evapotranspiration process reduces the amount of incoming solar and terrestrial radiation available to be absorbed by surface features and re-emitted as heat energy".[9]

Grass also helps lower temperature in parks; grass has a higher albedo than asphalt or most building roofs. Outside of the urban areas, rural and suburban land covers have cooler temperatures than the downtown, urban heat island area.

This situation becomes a cycle (see Figure 2-3) because increased temperatures in the city core result in increased energy consumption to mitigate the higher downtown temperatures. The increased energy consumption requires more power generation, which results in higher pollutant emissions, including greenhouse gases. These gases are known to contribute to global climate change and thus continuing this cycle of increased temperature, energy

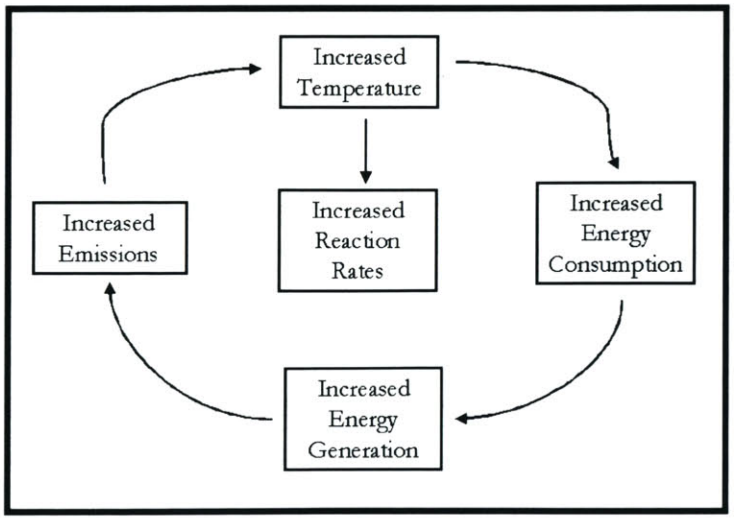

Figure 2-3: Cycle of the Urban Heat Island effect.

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[9] Stone, 2001.

consumption and energy generation.

Previous Research

The Heat Island Group at Lawrence Berkeley National Laboratory (LBNL) has done a significant amount of work on the UHI effect. They have collaborated with the US EPA, United States Department of Energy and National Aeronautics and Space Administration to characterize and quantify the UHI effect in U.S. cities such as Salt Lake City, Utah, Chicago, Illinois, Sacramento, California, Los Angeles, California and Atlanta, Georgia. The group has established how surface changes such as adding more green space and increasing albedo values of built-up spaces can result in reduced temperatures, reduced energy use and improved air quality.[10]

The LBNL group has quantified the benefit of UHI mitigation in Los Angeles. By adding lighter colored roofs and pavements and increasing the number of shade trees, they estimate a savings of 1.5GW of peak power from avoided air conditioning use and 10% reduction in smog.[11]

The United States Forest Service has worked on UHI issues as well. Gregory McPherson and James Simpson have looked at the issue of air quality specifically from the urban forest perspective. They take this perspective as another way to provide a valuation of natural resources such as urban trees.[12]

Researchers outside of the United States have also examined the UHI effect. In addition to the work that will be explored in the Chapter Three and Ernesto Jauregui's work in Mexico City, C.P. Tso has studied the UHI effect in Singapore and Kuala Lumpur, Malaysia.[13] Rohinton Emmanuel has looked at the issue in Colombo, Sri Lanka.[14]

The UHI effect has also been applied to the debate of high-density development versus low-density development. A recent presentation at an American Planning Association conference related air quality, temperature and land use planning and concluded that high density land development patterns contribute less radiant energy, thus contributes less to the heat island effect, than low density development patterns. Stone and Rodgers used parcel level data and determined a positive relationship existed between pervious and impervious areas of single-family residences and net

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[10] Akbari, 2001; Rosenfeld, 1997.

[11] Rosenfeld, 1996.

[12] McPherson, 1998; Simpson 1998.

[13] Tso, 1996.

[14] http://www.hdm.lth.se/TRAINING/Postgrad/AEE/papers/1999/16_AEE1999.pdf.

thermal emissions. See Figure 2-4. The amount of exposed surface area (without tree cover) has a positive relationship with temperature.[15] Specifically:

> Rather than the total parcel area, it is the quantity of exposed surface area that likely underlies the positive relationship found between parcel size and net thermal emissions. Although larger parcels tend to dedicate a greater proportion of the lot to tree canopy cover, these lots tend to have a greater uncanopied area as well. For example, if both an acre- and a 1/4-acre-sized lot exhibit a 50% tree canopy cover, the larger lot is exposing four times as much surface area (1/2 acre vs. 1/8 acre) to incoming radiation. This relationship is confirmed by a positive and significant correlation found between total parcel area and the area of the parcel not covered by tree canopy (r=0.70, p<.000).[16]

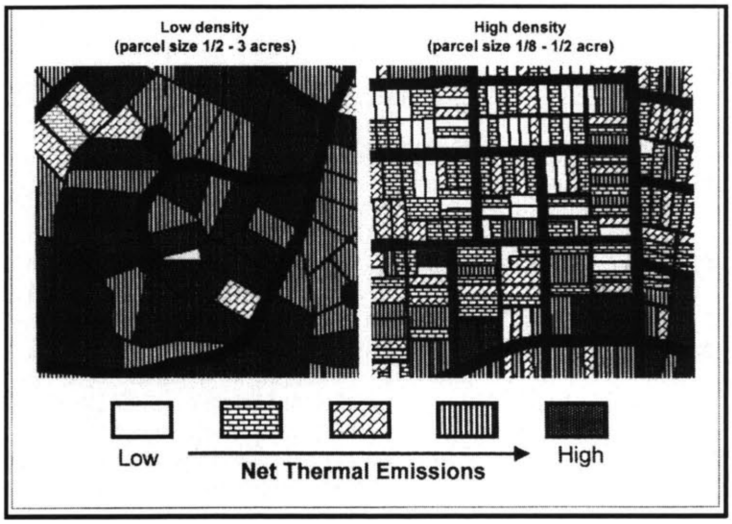

Figure 2-4: Net thermal emissions by development pattern (Source: Stone, 2001).

This led to two conclusions regarding urban design strategies to minimize UHI effects:

- Promotion of infill development
- Introduction of area-based tree canopy requirements.

Infill development focuses development in the central city core and reduces deforestation in the periphery areas. Tree canopy requirements involve planting a specified number of trees to mitigate the amount of land devoted to development. The tree planting pattern impacts temperature. It is not enough to simply grow a certain number of trees. According the Stone and Rodgers study, "a thin but well distributed canopy of trees is likely to be more thermally efficient than a dense cluster that leaves a large proportion of the property completely unshaded."[17]

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[15] Stone, 2001.
[16] Ibid.
[17] Ibid.

UHI Mitigation Strategies

Bringing together the work described above, it is apparent that using UHI mitigation strategies to improve air quality can have a significant impact on city design. Using the UHI framework to examine air pollution brings about a more holistic approach to laying out the plan of a city. This approach to city design links energy consumption and livability issues that are not typically considered when proposing physical plans. The UHI mitigation strategies outlined below reduce temperature in urban environments by the process illustrated in Figure 2-5.

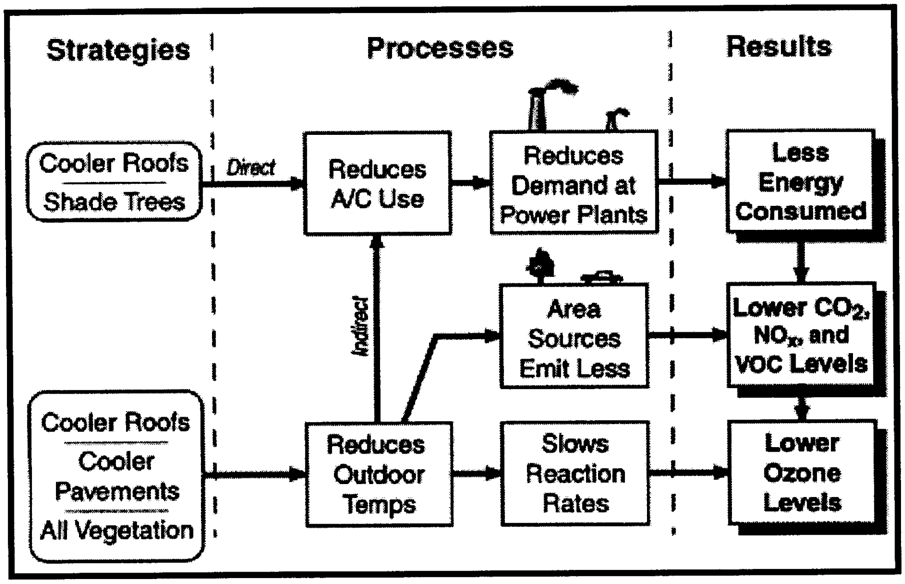

Figure 2-5: Process of UHI mitigation (Source: Akbari, 2001).

Green Roofs

In constricted spaces like urban areas, limited possibilities exist to increase the amount of green space. A creative solution to this restriction makes use of a technique frequently used in Europe and particularly Germany. Green roofs are contained green spaces that include non-potted and potted plants landscaped together directly on the roof of a building.[18] Special rubber membranes and growing mediums are used to prevent structural damage to the building roofs. Two types of green roofs exist – intensive and extensive.

Intensive Green Roofs (roof gardens): These high-maintenance roofs allow for foot traffic and involve more elaborate landscaping plans including trees, shrubs and bushes. Consequently, more sophisticated growing mediums are required.

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[18] http://www.peck.ca/grhcc/about.htm.

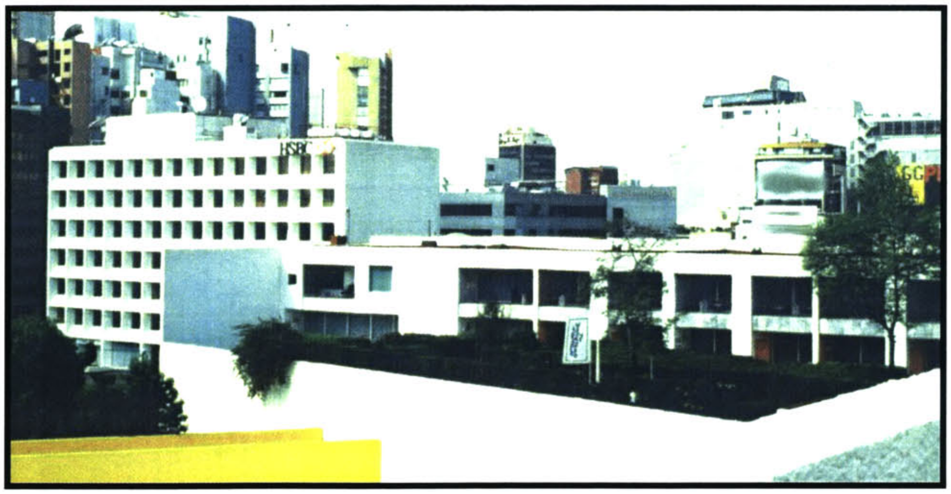

Figure 2-6: Intensive green roof – Camino Real México (Source: personal photo).

Extensive Green Roofs (greenroofs): These roofs require less maintenance. They are generally not open to foot traffic and have relatively simple landscape designs. With low-maintenance plants growing, they utilize lightweight growing mediums and costs are kept to a minimum.

Figure 2-7: Extensive green roof (Source: www.hrt.msu.edu/faculty/ Rowe/Green_roof.htm).

See Figure 2-8 for a comparison of these two types of roofs. For purposes of this study, intensive and extensive roofs are considered interchangeable because both have the same effect of lowering surface temperature and thus reducing the UHI impact in a city.

According to Green Roofs for Healthy Cities, a Canadian organization focused on bringing green roofs to North America, Europe's legislation and financial commitment to green roofs has led to a public understanding of green roof benefits.[19] "In some parts of Germany, new industrial buildings must have green roofs by law; in Swiss cities, regulations now require new construction to relocate the area of greenspace covered up by the building's footprint to the rooftop - and even existing buildings, some hundreds of years old, [and] must convert 20% of their roofspace to pasture."[20] In North America, there is little understanding of green roofs and an undeveloped market prevents potential suppliers and consumers from interacting.

<u>Benefits of Green Roofs[21]:</u>

- Improved Air Quality
  - -Green roofs directly improve air quality by filtering air moving above it. 1 m^2 of grass roof can remove between 0.2 kg of airborne particulates from the air every year.
  - -1.5 m^2 (10.76 ft^2) of uncut grass, produces enough oxygen per year to supply 1 human with their yearly oxygen intake requirement.
- Temperature Regulation
  - -Through evapotranspiration, plants use heat energy from their surroundings (approximately 592 kcal per L of water). One m^2 (10.76 ft^2) of foliage can evaporate over 0.5 liters of water on a hot day and on an annual basis the same area can evaporate up to 700 liters of water.
  - -On a summer day, the temperature of a gravel roof can increase by as much as 77°F, to between 140 - 176°F. Covered with grass, the temperature of that roof would not rise above 77 °F, thus resulting in energy cost savings.
  - -Rooms under a green roof are at least 37.4 - 39.2 °F cooler than the air outside, when outdoor temperatures range between 77 - 86 °F.
- Water
  - -In summer, depending on the plants and growing medium, green roofs retain 70-80% of the precipitation that falls on them; in winter, they retain between 25-40%. For example, a grass roof with a 4-20 cm (1.6 - 7.9 inches) layer of growing medium can hold 10-15 cm (3.9 - 5.9 inches) of water.
  - -Green roofs reduce the amount of stormwater runoff and also delay the time at which runoff occurs, resulting in decreased stress on sewer systems at peak flow periods.

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[19] http://www.peck.ca/grhcc/about.htm.

[20] http://www.cityfarmer.org/roofmonica61.html.

[21] http://www.peck.ca/grhcc/public.htm#temperature.

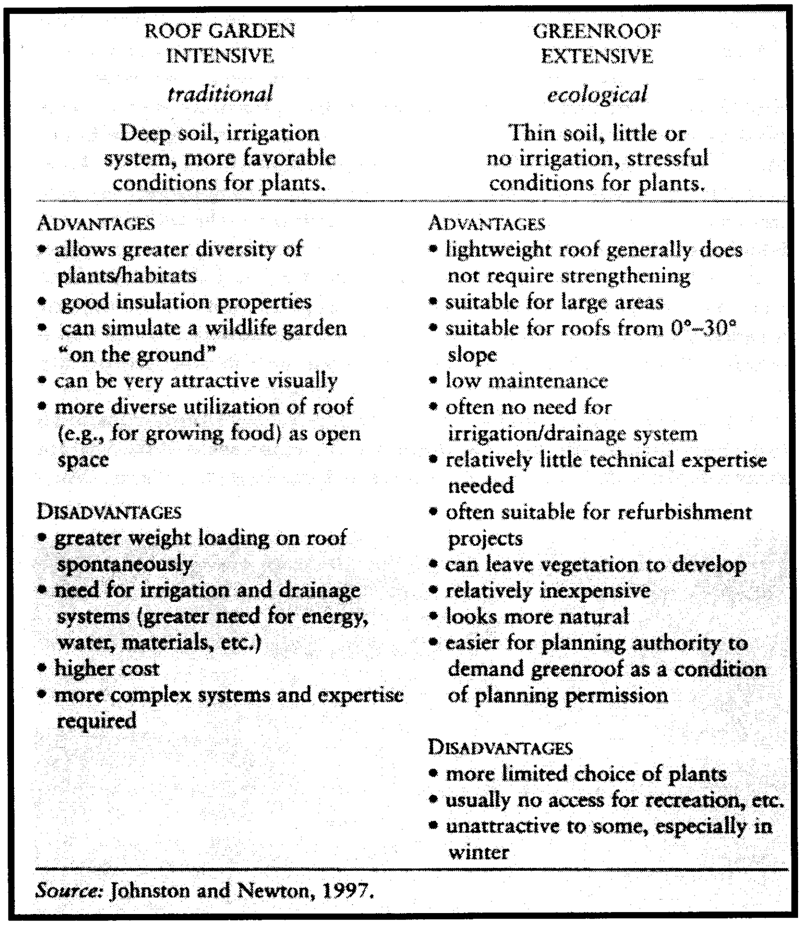
- Social Benefits

  -Beautifies the built environment and increases investment opportunity.

  -People living in high-density developments are known to be less susceptible to illness if they have a balcony or terrace garden..

  -The creation of shared gardens, like the rooftop garden on top of the Mary Lambert-Swale housing project in Toronto, allows residents to feel ownership of their building and meet neighbors in a relaxed setting.

  -Green roofs can provide new opportunities for urban agriculture.



ROOF GARDEN INTENSIVE	GREENROOF EXTENSIVE
traditional	*ecological*
Deep soil, irrigation system, more favorable conditions for plants.	Thin soil, little or no irrigation, stressful conditions for plants.
ADVANTAGES • allows greater diversity of plants/habitats • good insulation properties • can simulate a wildlife garden "on the ground" • can be very attractive visually • more diverse utilization of roof (e.g., for growing food) as open space	ADVANTAGES • lightweight roof generally does not require strengthening • suitable for large areas • suitable for roofs from 0°–30° slope • low maintenance • often no need for irrigation/drainage system • relatively little technical expertise needed • often suitable for refurbishment projects • can leave vegetation to develop • relatively inexpensive • looks more natural • easier for planning authority to demand greenroof as a condition of planning permission
DISADVANTAGES • greater weight loading on roof spontaneously • need for irrigation and drainage systems (greater need for energy, water, materials, etc.) • higher cost • more complex systems and expertise required	DISADVANTAGES • more limited choice of plants • usually no access for recreation, etc. • unattractive to some, especially in winter

Source: Johnston and Newton, 1997.

Figure 2-8: Comparison of intensive and extensive green roofs (Source: Beatley, 2000).

An additional benefit of lowering temperature is that smog formation is reduced. "Increased air temperature over roof surfaces contributes to the chemical reaction that creates low atmospheric ozone, which is the primary component of smog."[22]

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[22] Schloz-Barth, 2001.

Albedo Change

Increasing albedo values of surfaces also helps lower surface temperature. This technique dates back to ancient times and is still practiced in Mediterranean and Middle Eastern cities where buildings must still be whitewashed.[23] Many of these cities and towns look like areas of snow covered hillsides, with the white surfaces reflecting the strong sunrays. Lowering surface temperature reduces the demand for power to cool interior spaces. The idea of albedo change has been applied to two distinct city features – rooftops and paved surfaces such as roads and parking lots.

Rooftops: The ambient and surface air temperature difference between light and darker colored rooftops is dramatic. Dark colored surfaces can have a difference as large as 50°C between surface and ambient air.[24] The warmer air above dark roofs contributes to an increased demand in indoor air-cooling. A study by LBNL showed that on a hot summer afternoon, increasing albedo from 0.20 to 0.60 decreased the temperature by 25°C.[25]

In the United States, the state of Georgia encouraged the use of white roofs by implementing the White Roof Amendment as part of their local and state energy efficiency building code requirements. The amendment, approved in the late 1990s, "requires the use of additional insulation for roofing systems whose surfaces do not have test values of 75 percent or more for both solar reflectance and emissivity."[26] Organizers of this amendment came from academia, roofing specialists and community members. This legislation sets an example for other state and local governments.

Higher albedo value roofs result in more reflected solar radiation thus decreasing surface temperature. This technique is not limited to residential and commercial buildings. There are several examples of white roofs in the industrial sector. A Mercedes-Benz factory in Alabama and a Helen of Troy plant in Texas both use a white roof membrane roof. In Mexico, Tyco International in Matamoros and Kodak in Guadalajara implemented white roofs to conserve energy.[27] Considering the

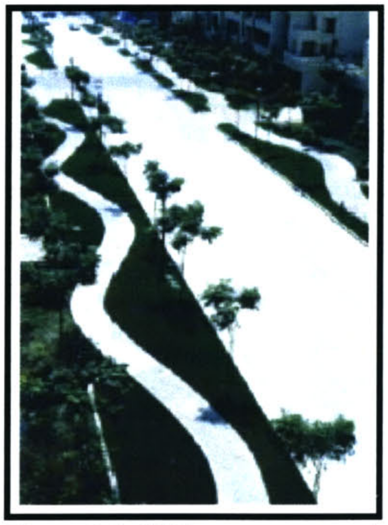

Figure 2-9: White pavement and trees (Source: VanGeem, 2002).

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[23] Rosenfeld, 1997.

[24] Akbari, 2001.

[25] Akbari, 2001.

[26] http://www.wernergc.com/georgia_white_roofing_amendment.htm.

[27] http://www.twin-plant-news.com/issues/oct01/feature.htm.

roofs of industrial plants is important because those structures often cover a significant amount of surface area with little vegetation to help mitigate increased temperature.

White streets and parking lots: The same principle used with white rooftops applies to white streets and parking lots. Lighter surfaces reflect more solar radiation than darker surfaces. Work by LBNL's Heat Island group shows replacing asphalt roads with portland cement concrete has higher initial costs, but cement concrete roads last longer.[28] The ubiquitous asphalt pavement type has a service life of 15 years while cement has a life type of 25 years.

As is the case with green roofs, the market for white roofs in North America is immature and market barriers exist that prevent more extensive use of white streets and pavements. In addition, there is a "cultural barrier" that perpetuates the idea that black pavement is better.[29] Fresh black asphalt is seen as high-quality pavement and contractors actually add black carbon because of consumer expectations.[30]

It is interesting to note that the darker surfaces of roads, pavements and roofs are more prone to damage as compared to lighter-colored surfaces. Darker surfaces absorb more heat and are more likely to suffer the effects of thermal stress. This stress can shorten the life of these dark-colored surfaces as evidenced by the fact that white asphalt shingles last longer than dark asphalt shingles.[31]

Urban Trees

In addition to adding green space by adding green roofs to existing buildings and new construction, integrating more urban trees into the cityscape can help mitigate the UHI effect. In Sacramento, a tree-planting program sponsored by a local utility evaluated the impact of additional trees in a residential area. The study found direct building wall and roof shading decreased energy consumption from reduced air conditioning use in a residential area[32].

In addition to direct effects on the UHI effect and consequently indirect effects on air quality, urban trees can directly improve air quality. A study in Frankfurt, Germany showed streets with trees had 3000 dirt particles per liter of air while a nearby street without trees had an air pollution count of 10,000-20,000 dirt particles per liter of air.[33] Figure 2-10 illustrates this idea.

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[28] Ting, 2001.
[29] Ibid.
[30] Ibid.
[31] Bretz, et al., 1998.
[32] Simpson, 1998.
[33] Johnson, 1993.

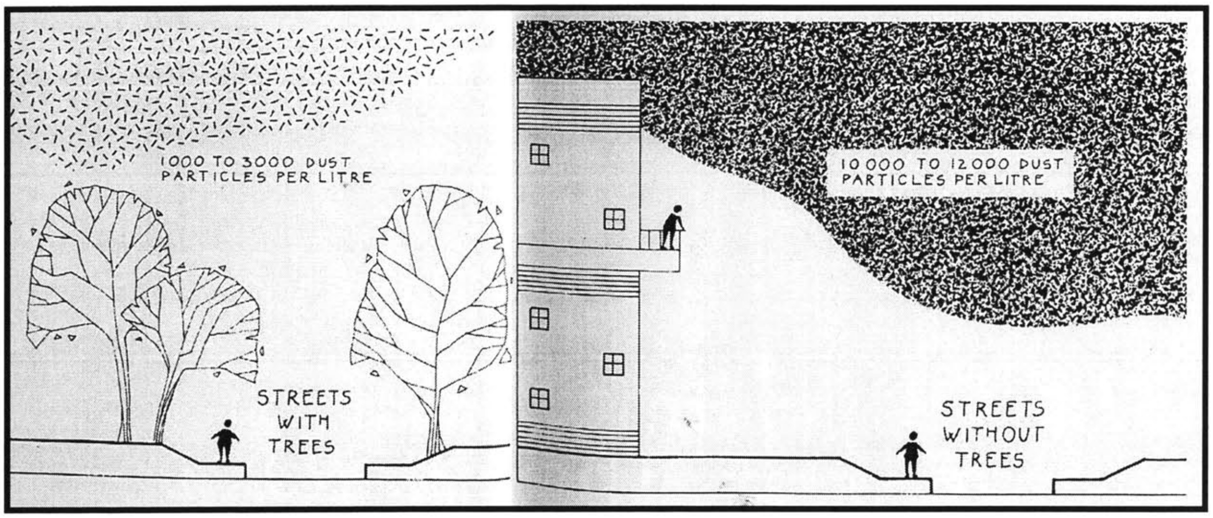

Figure 2-10: Impact of trees on air quality (Source: Johnston, 1993).

Urban trees not only have the potential to improve urban air quality, but in addition, certain tree species can actually contribute to air pollution. Certain trees species release VOCs such as isoprene, monoterpene, and alpha-pinene. These compounds help contribute to the formation of ozone. To ensure urban tree plantings are effective in improving air quality, it is necessary to use biogenic emissions as a criterion in selecting what trees to plant. Appendix B is a list of low emission trees with a hardiness rating similar to the conditions found in Mexico City.

Summary

At the intersection of temperature, land use and air quality lies the Urban Heat Island concept. Air quality is influenced by temperature and temperature is thus related to land use type. Building on previous research and bringing together UHI mitigation strategies like albedo modification, integrating more urban trees and adding green roofs can help decrease temperature and therefore improve air quality. The next chapter examines the practical application of UHI mitigation strategies in Singapore and Tokyo.

Chapter Three: UHI Mitigation in Practice: Tokyo and Singapore

Across the globe effective implementation of UHI mitigation strategies are integrated into city plans and air quality improvement programs. In the United States, cities as small as Austin, Texas to cities as large as Los Angeles consider UHI strategies in their city plans. Outside of the United States, cities at a variety of latitudes and climates consider the UHI framework as a way to improve city design and air quality. To facilitate discussion of the application of a UHI mitigation framework to Mexico City, Singapore and Tokyo are used as case studies of UHI mitigation in practice.

Case Study Analysis

Using the case study method to reveal potential implementation issues of UHI mitigation increases the breadth of factors for evaluation. These social science factors can expose influences that might be apparent from a quantitative analysis of satellite imagery or GIS data.

Case Study Cities: Tokyo and Singapore

The two case study cities both have UHI mitigation strategies in place. Both have acknowledged the importance of temperature as a factor in air quality. Financial and resource support have been adequately provided to determine the potential impact of UHI work.

Tokyo was chosen as a case study example for Mexico City because it is a megacity with an extensive UHI plan and furthermore, there is support from the Tokyo municipal government and Japanese national government. There have been a number of studies quantifying the UHI effect in Tokyo and obtaining this data was less difficult compared to other cities around the world.

Singapore is an island-nation where the intersection of air quality, land use and urbanization is crucial. It sits at approximately the same latitude as Mexico City and it faces obvious limits to urban sprawl and land use. Singapore has a reputation for bringing together best practices from different cities and incorporating them into the city's own landscape. Its city planners study which processes or behaviors are most effective in other areas, customize the best options to Singapore and implement them in the city. Several studies have quantified the UHI effect in Singapore.

In each of the case studies, a few key elements are highlighted:

- Motivations for UHI plan in city
- Key players
- Implementation plan

- Results of city-specific studies
- Public perception of plan
- Results of plans

Case Study One: Tokyo

Tokyo's status as a megacity facing a situation of increasing urbanization and consumption made it suitable city for an Urban Heat Island mitigation case study analysis. The Tokyo municipal government and Japanese national government together play an active role in UHI mitigation. Their financial and political support has contributed to the public's awareness of the UHI phenomenon and has allowed for many studies of UHI assessments in the city.

Motivations for UHI Plan:

Over the past 100 years, the average temperature in Tokyo has risen 5.2°F degrees while the rest of the world's average temperature rose 1°F degree.[34] In the face of rising consumption rates and increasing population, the city has determined this temperature increase must be slowed in order to manage energy consumption levels and air quality standards.

Despite having only 14% of downtown Tokyo in urban greenery, less than New York or London, the city finds value in the urban greenery strategies that are used to help mitigate the UHI effect. From personal experience, it appears the many citizens of Tokyo appreciate green space. The government understands this and has put a premium on public green space.

Key Players:

Tokyo has made significant progress in terms of UHI mitigation plans. Much of this progress has to do with the variety of stakeholders involved. Key players include:

- National government and associated ministries
- Tokyo municipal government
- Organization for Landscape and Urban Greenery Technology Development (Urban Green Tech)
- University researchers
- Private developers.

Urban Green Tech is a semi-governmental organization. Much of its work consists of contract work from Tokyo and Japanese governments. The range of players involved with UHI mitigation have helped bring proposed solutions to reality in the city.

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[34] Brooke, 2002.

Implementation Plan:

In 2000, the municipal government created the Green Tokyo Plan. This plan attempts to reduce the impacts of the UHI effect by restoring green space in the city, preserving the current green space in the city and protecting agricultural and forested land.

The plan also regulates developments of a certain size and requires the provision of green space and in some cases, green roofs. Specifically, green areas are required for new construction in an area of 1,000m^2 for private facilities and in an area of 250m^2 for public facilities. Also, new construction with a total floor area larger than 10,000m^2 must include rooftop greenery.[35] City officials want to eventually make "roof gardens as common for buildings as stairways."[36]

At the national level, the government has set up tax incentives for construction that includes rooftop greenery. The government also provides subsidies for rooftop gardens on public buildings. There is limited government support for privately owned green roofs.

Figure 3-1: Example of a green wall: Acros Fukuoka building in Tokyo (Source: Ooka presentation).

Results of Tokyo UHI Studies:

Urban Green Tech has done several studies for the federal and city government in attempting to quantify the effects of urban greenery on UHI effects.

A few of their findings include:

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[35] http://www.kankyo.metro.tokyo.jp/kouhou/english2001/index.htm.

[36] Brooke, 2002.

- Trees are more effective than grass at reducing ambient air temperature because they have higher evapotranspiration rates
- A 100-meter buffer space around green areas continues to experience the cooling effects.
- Green areas near water are more effective in lowering temperature than green space away from water.

A recent study by Urban Green Tech worked out a "green-out" scenario to reduce the UHI effect in Tokyo. Their scenario included increasing building height on proposed construction (building up rather than wide), increasing grass and tree cover and introducing more green roofs and walls on existing buildings. Their scenario increased urban greenery cover from 27% to 39.5% and predicted an associated decrease in temperature that would bring average temperature to a level that existed 10 years ago.

Public Awareness:

"Urban Heat Island" is now a common phrase in Tokyo as the public is frequently exposed to UHI mitigation strategies. In the case of Shiodome, one of the biggest development projects in the Tokyo Bay area, the media reported the development's measures to counteract the heat island effect.[37] The public is also made of aware of UHI mitigation strategies in the marketing materials of Japanese developers. Marunouchi, a high-end real estate developer in Tokyo since 1890, advertises its urban greenery plans alongside promotion of its advanced information technology infrastructure.[38]

Interest in UHI mitigation can also be seen with the increased interest expressed for rooftop gardens at landscape firms. In 2001, Greenich Garden created 50 rooftop gardens. By the end of summer 2002, the same firm had 200 orders for rooftop gardens.[39]

Case Study Two: Singapore

Singapore stands as an example of a city facing severe limits to its urban sprawl. As an island-nation, its city limits are constrained by the very limits of the island itself. Singapore's Urban Heat Island Mitigation plan is examined as a case study for Mexico City because the cities are at similar latitudes and because Singapore, with a tightly controlled central government, exists as a stark contrast to the less-than ordered management of Mexico City.

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[37] Inoue, 2003.
[38] Marunouchi, 2003.
[39] Brooke, 2002.

Singapore brings together the best practices of cities around the world and unites them in the city. At even the most superficial level, this trait is apparent when one sees the red double decker buses of London in the same frame as the Duck Tours of Boston.

Motivations for UHI Plan:

In the 1960s, Singapore adopted a "Garden City" approach to urban development. This intentional approach to urban planning led to a focus on preserving current green space and increasing the amount of green space in the city.[40] Today, the city feels development pressure on the limited amount of developable land available. In addition, the city faces increasing energy consumption. The World Wildlife Fund classified Singapore as the 4th largest per capita energy consumer in the world.[41]

Key Players:

There are a few key players involved with the UHI mitigation plan. These organizations are:

- Singapore government via National Parks Board and Housing Development Board (HDB)
- National University of Singapore (NUS)
- General public.

At NUS, Dr. Wong Nyuk Hien is particularly active in the area of "skyrise greening" and the UHI effect.

Implementation Plan:

Most of Singapore's efforts to reduce the UHI effect focus on adding green space. In the New Concept Plan 2001, Singapore's 50-year plan for urban development, the city envisions utilizing land space more efficiently and being a "greener city."[42] The plan has the following "green" goals:

- Almost doubling the amount of green space from 2500 ha to 4500 ha
- Preservation of rustic areas in natural state[43]
- Extending the park connector network to link parks with town centers, sports complexes and homes.

In addition to these strategies, the HDB has already implemented rooftop gardens above several carparks.[44] This is a noteworthy step as approximately 85% of Singapore residents live in

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[40] Wong, 2002.
[41] Nathan, 1999.
[42] Fernandez, 2001.
[43] Ibid.
[44] Yeo, 2001.

HDB public housing.[45] Awareness of UHI mitigation at the HDB is significant because future apartment buildings and buildings scheduled for renovation could be designed with green roofs and additional green space.

In the private sector, commercial buildings, hotel developments and private developments all have examples of rooftop gardens.

Results of Singapore UHI Studies:

C.P. Tso at Nanyang Technological University has shown there is a difference of 3°C between the rural and urban areas of Singapore and that temperature at the low density city center was warmer than areas of high-rise residential development.[46] This observation is consistent with the work by Stone and Rodgers cited in Chapter Two that compact, high density areas could be a design strategy that mitigates the effects of UHIs.

In Singapore, power generation creates the largest source of carbon dioxide emissions, and in commercial and office developments, air conditioning needs consume the largest amount of energy.[47] In this environment, steps that commercial developments take to reduce air conditioning usage could have an impact on the level of carbon dioxide emissions. Work by NUS and the National Parks Board show that rooftop gardens can mitigate the UHI effect. Their findings about rooftop gardens include:

- Air temperature reduced by as much as 4°C
- Potential energy savings from air conditioning could result from insulating buildings
- Helps improve air quality.

Singapore is still working towards making them more common in the city. The researchers indicate legislation and building code guidelines could help bring more green roofs to the city. As of the end of 2002, the National Parks Board and Urban Development Authority were working together to include incentives for rooftop greenery in development guidelines.

Public Awareness:

The impact of UHI mitigation strategies, particularly rooftop gardening, is not lost on the residents of Singapore. From skyrise garden competitions to a hospital growing vegetables on the

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[45] http://www.hdb.gov.sg.

[46] Tso, 1996.

[47] Nathan, 1999.

roof, these urban greenery stories are covered in the Singaporean media and residents are made aware of the efforts of public, private and academic pursuits to reduce the UHI effect in Singapore.

At the Changi General Hospital, vegetables grown on the hospital's roof help feed patients. This garden provides the additional benefit of reduced energy bills. The hospital has reduced its utility bills by $800,000.[48]

HDB residents were put to the test on their rooftop gardens. The agency sponsored a competition to determine who had the best-looking garden. This kind of promotion not only furthers the beautification of the city, but it also enhances awareness of urban greenery importance.

Significant foreign investment has been attributed to green beautification.[49] Singapore has been able to successfully implement this urban greening strategy into its city growth plan. Throughout the city, visitors see enormous plant potters built into the city infrastructure and buildings (see Figure 3-2). Massive flowerpots overflowing with blooms are built into street and highway overpasses. Boulevards are lined with large flowering trees. These attractive landscaping techniques not only help draw foreign investment, but add to the list of UHI mitigation strategies the city employs.

Figure 3-2: Example of Green Walls in Singapore (Source: Wong, 2002).

Summary of Case Studies

Building on the practical UHI mitigation experience gained by Tokyo and Singapore, Mexico City can customize its own UHI mitigation plan. In Tokyo, a strong quasi-governmental organization, Urban Green Tech, has helped propel the UHI mitigation issue to the attention of policy makers and the general public. Their work on effective UHI mitigation design strategies has concluded trees are more effective than grass at reducing ambient air temperature, a buffer space exists around green spaces and green space near water reduces ambient air temperature better than green space without a nearby waterbody.

In Tokyo, mandatory green roofs and space for developments of a certain size have increased green space in the city and brought more UHI awareness to the general public. This

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[48] Nathan, 1999.

[49] Sorenson, 1997.

awareness feedsback into the system as private developers promote their attentiveness to environmental concerns by marketing their green building practices.

In Singapore a coordinated effort between different agencies (NPD and HDB) has made UHI mitigation a more prominent issue in urban planning of the city. In addition, Singapore separates itself by framing the benefits of UHI mitigation practices beyond only air quality improvement. They see urban greenery as a way to make the city beautiful and welcoming, and as a method of attracting foreign investment.

Building-level reductions in energy consumption are apparent as a result of green roofs or white surfaces. It is too early to measure the citywide success of reducing metropolitan ambient temperature of the Tokyo and Singapore UHI mitigation plans because these cities' plans are still in a nascent stage and need more time and more extensive implementation. Until more data can be collected and accumulated, evaluations of the UHI plans must rely on piecing together energy savings from individual buildings and assessing the public's awareness of the issue. As the public becomes more interested and involved, the implementation of the UHI mitigation plans are likely to accelerate.

Chapter Four: UHI Mitigation Plan For Mexico City

This section focuses on assessing the application of the UHI concept to Mexico City. The work of Dr. Ernesto Jauregui, a pioneer in UHI work in Mexico City, will be described and used as a backdrop for this study. The effects of a Mexico City UHI mitigation strategy will be discussed based on a hypothetical UHI mitigation scenario.

Assessing the UHI in MC

Previous Research:

In the mid 1980s, Dr. Jauregui documented the gradual increase in Mexico City's average annual temperature. Recently, with updated data, he has shown a gradual temperature increase in the past 100 years (1900 to 2000). As Figure 4-1 shows, the average annual temperature has increased from 14.8°C in 1900 to 16.8°C in 2000.

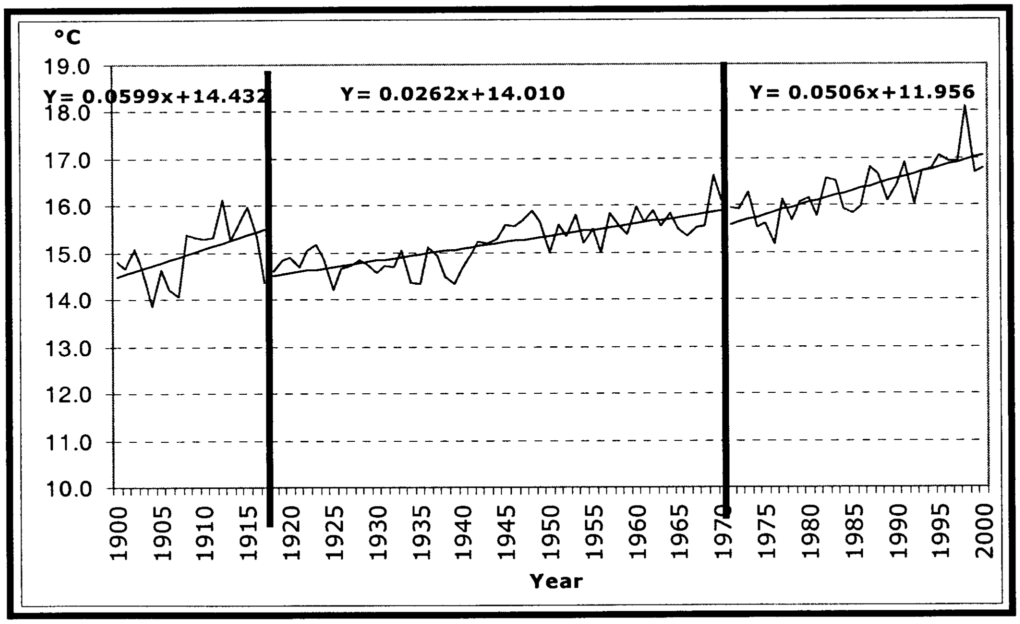

Figure 4-1: Average annual temperature in Mexico City.[50]

According to Dr. Jauregui, from 1917 to 1969, the mean annual rate of temperature change was 0.3°C /decade; in the last third of the 20th century, the mean annual rate of temperature change increased to 0.5°C /decade, an almost two-fold increase.[51] It is likely the cause of this temperature increase is the UHI effect and if current patterns continue whilst the city continues to expand its

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[50] Dr. Jauregui chose the data breakpoints for undocumented reasons.

[51] Jauregui, 2003.

urbanized area, average temperature will probably grow by one degree Celsius by 2020. It is noteworthy that in the past century, the earth's average temperature rose by 1°F degree.[52] The predicted temperature increase in Mexico City could result in more heat waves.[53]

In a recent study published in *Atmosfera*, Jauregui concluded that the climate of Mexico City could change climate categorizations in the ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) scale to a warmer category.[54] This is an unusual condition and according to Jauregui, warrants the need for Mexico City officials to employ strategies to mitigate the predicted warmer temperatures.[55]

Building upon what Jauregui has determined, the next portion of this study attempts to characterize the relationship between surface temperature and land use using remotely sensed data and then determine if a set of UHI strategies can have a measurable effect on temperature. Potential impacts on energy use and consequently air quality will be examined the next chapter.

Land Use and Surface Temperature:

Previous studies in cities such as Sacramento and Salt Lake City have used orthorecified aerial photography to characterize the urban fabric of each city.[56] This method allows for a detailed classification of land use and consequently, more subtle distinctions in surface temperature can be found among different land uses. Aerial photography was not available for this study of Mexico City. Landsat 7 satellite imagery was used instead.

Landsat 7 Satellite Imagery:

Landsat 7 satellite imagery is available jointly from the United States Geological Survey (USGS) and the National Aeronautics and Space Administration. The Landsat 7 system breaks down the Earth into 57,784 scenes, each 115 miles (183 kilometers) wide by 106 miles (170 kilometers) long. The satellite completes its full coverage of the Earth in 16 days. Consequently, Landsat 7 takes a new picture of an area every 16 days. The Metropolitan area of Mexico City lies between two Landsat 7 scenes (Path 26, Row 46; Path 26, Row 47). Most of the city is contained within the Path 26, Row 47 scene. Landsat 7 passes over Mexico City mid-morning each cycle. This means only daytime urban heat island characteristics would be detected.

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[52] Brooke, 2002.
[53] Jauregui, 2003.
[54] Jauregui and Tejeda, 2001.
[55] Jauregui, 2003.
[56] Akbari, 1999; Akbari, 2001.

Landsat 7 data includes 7 bands of data. Each band is sensitive to a specific range of spectral bandwidths. A composite image of bands 1-5 and 7 are used for land use classification. Band 6 is used to derive temperature data. Spatial resolution is 30 meters for bands 1-5 and 7 and 60 meters for band 6.[57]

Several UHI studies have used Landsat 7 data[58] to describe a relationship between the land use and temperature. Landsat data allows a larger and more uniform sampling than *in-situ* data. It has less spatial detail than aerial photography, but data storage and management requirements are much less intensive. In addition, in software packages like IDRISI, it is a simple process to convert thermal information in band 6 to degrees Fahrenheit.

A search for Landsat 7 satellite imagery and GIS data was limited by time and financial constraints. A recent image of Mexico City was purchased, but because of administrative difficulties, the data arrived too late for this analysis. A substitute scene from a preliminary analysis was used instead. This image was acquired on 7 March 1989.

Image Processing:

From the seven bands of the Landsat 7 scene, land use classifications and surface temperature were derived.

Land Use: Lacking adequate land use GIS data to make land use classifications, informal interviews with a Mexican colleague[59] were conducted to determine what features matched what land use type. This procedure involved identifying:

- major green spaces in the city
- large urban residential neighborhoods
- industrial areas
- water bodies
- commercial areas, and
- mountains and volcanoes

located on Instituto Nacional de Estadistica Geografia e Informatica (INEGI) hard copy maps. Next, corresponding areas in a composite band Landsat 7 scene (Figure 4-2) were identified and signature files were developed in IDRISI.

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[57] USGS, 2003.

[58] Lougeay, 1996.

[59] Antonio Perez, a Policy Subdirector at the Mexico Ministry of Energy, is a native of Mexico City.

Based on these signature files, a supervised classification of land cover of bands 1-5 and 7 was performed. IDRISI had difficulty distinguishing between residential, commercial and industrial areas so the signature files were further refined to improve the supervised classification.

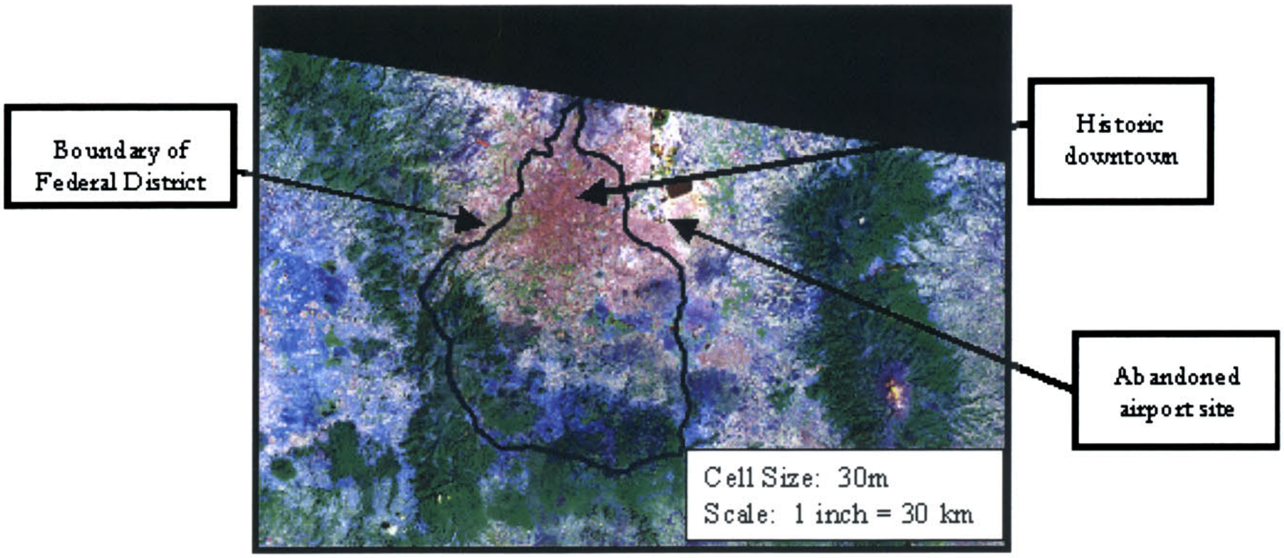

Figure 4-2: False color composite image of bands 1-5 and 7.

After further revision, the land use classifications were reduced to 4 categories. These land use categories were:

- Water features
- Urban/industrial
- Green space
- Barren land.

Figure 4-3 breaks out the generalized land use pattern.

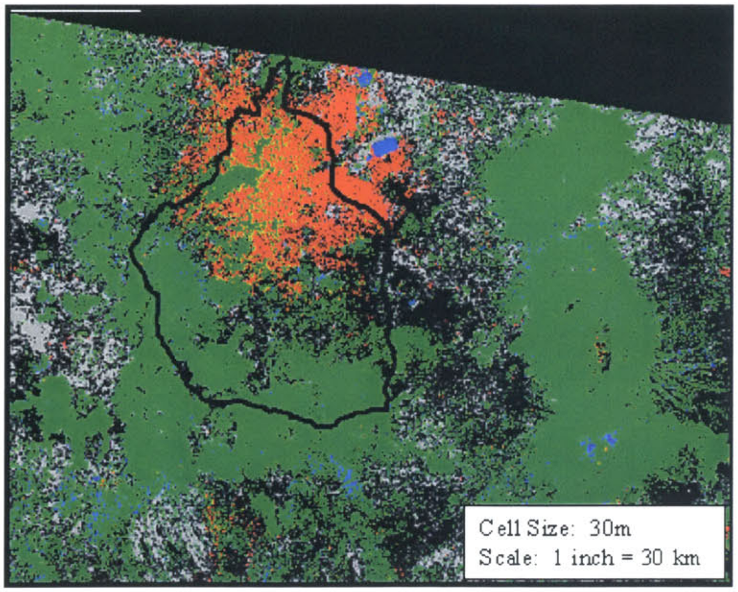

Figure 4-3: Results of land use classification. Green is green space, red is urban/industrial, blue is water and gray is barren land.

Surface Temperature: Land surface temperature was derived from band 6. Figure 4-4 indicates the intensity of energy emitted from the surface as a function of temperature. IDRISI converts this data into blackbody temperature data in Kelvin. The blackbody temperature data was then multiplied by material-specific emissivity values and the results were converted to degrees Fahrenheit.

With surface temperature for the entire area calculated, the average surface temperature was extracted based on the 4 land cover types created.

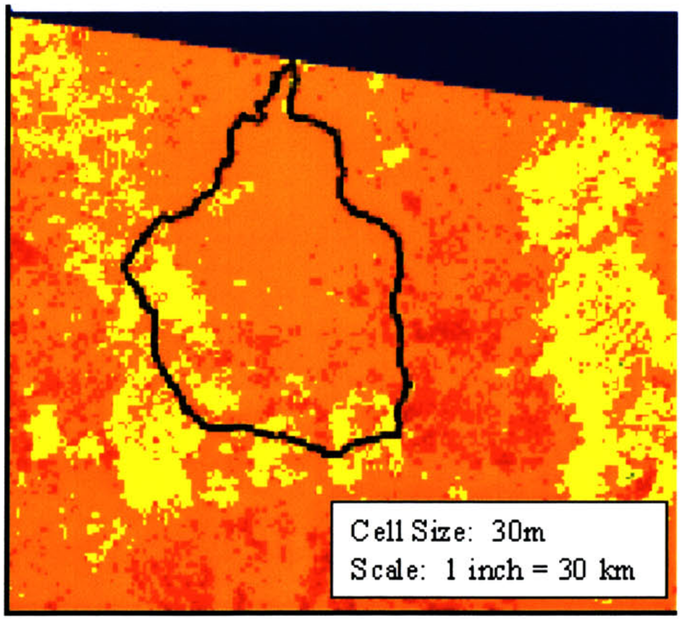

Figure 4-4: Thermal image based on band 6. Light areas are cool; dark areas are warm.

Urban areas had a higher average temperature (72°F) than public and private green areas (63°F) in the city. Barren land had a higher average temperature (84°F) than urban areas (72°F).

Table 4-1: Average temperature categorized by land use classification

Land Use	Temperature (°F)
Water	58.49
Urban/industrial	72.35
Green space	62.75
Barren land	84.15

Image Analysis:

Based on a regression analysis between surface temperature and land use, 51% of the temperature variation is explained by land cover variation. Figure 4-5 describes the variation in temperature values across the land use categories. The water and barren land categories have a relatively small range of temperature variation compared to the urban and green space categories. Significant overlap between the spectral values of green space in the city and green area on the mountains/volcanoes surrounding Mexico City existed and probably confused the classification and resulted in a such a wide range of temperatures in the green space category. The range of temperature values could be reduced if the green space classification could be refined and by removing the mountains out of that category.

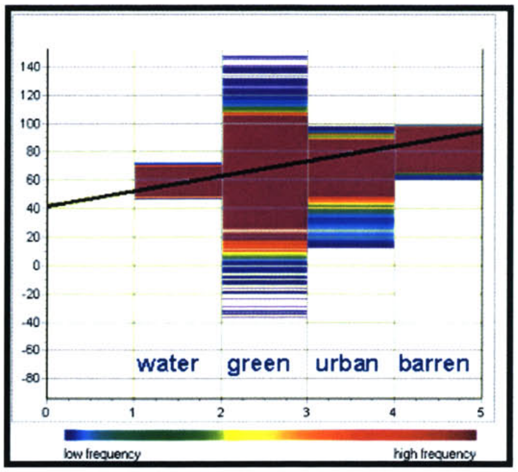

Figure 4-5: Temperature variation by land use category.

Lacking detailed land use data to improve the green space classification, the area of the Federal District was isolated and temperature by land use cover was extracted again. Restricting the analysis to only the Federal District removed the green space over the mountain range that likely confused the classification.

Figure 4-6 displays variation in temperature by land use category for the Federal District area only. For all the categories, the range of temperature values got tighter when the analysis excluded the mountain temperatures. In particular, the green space category has a reduced range of temperature values compared to the original temperature variation graph. This tighter range of green space temperature is better representation of what green space temperature is in the city because the mountain green space temperature values are excluded.

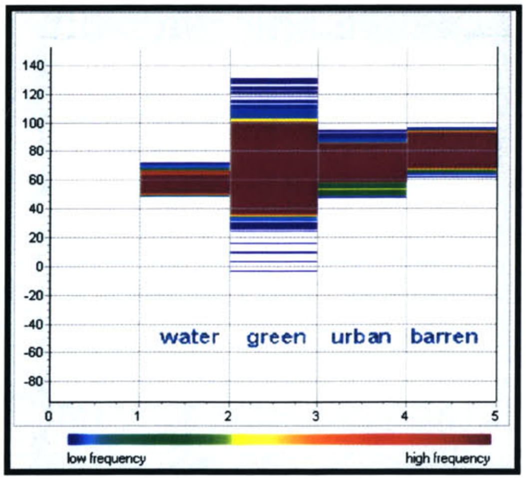

Figure 4-6: Temperature variation by land use category; Federal District only

A temperature versus distance from the city center was plotted to determine if a UHI profile similar the one in Figure 2-2 could be derived from this image of Mexico City. This profile (Figure 4-7) showed that temperatures decreased as land use changed with distance from the city core.

In this case, a line was drawn from the approximate area of the Zocolo, Mexico City's historic city center, out to the region of Chapultepec Park. As can be seen from the plot below, temperature decreased as distance from the city center increased.

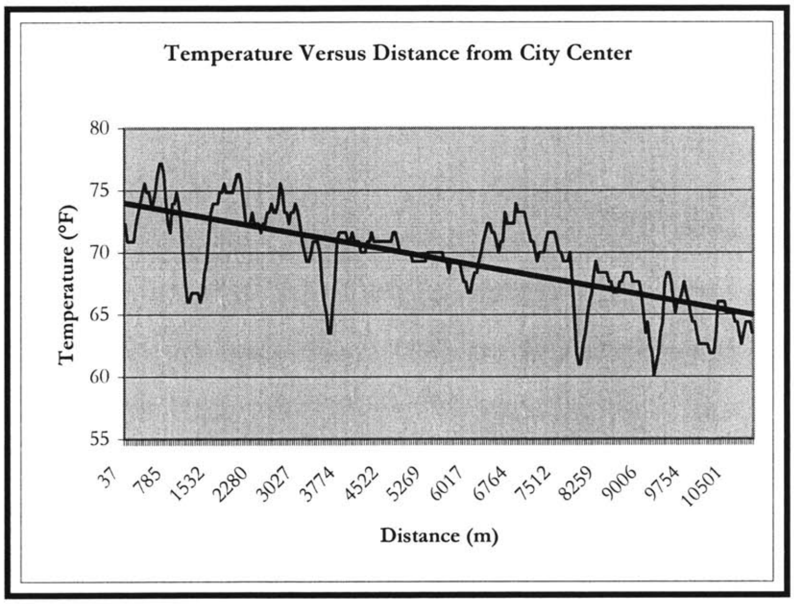

Figure 4-7: Temperature versus distance from Mexico City center.

Sharp increases and decreases in temperature are attributed to random variations in the data and in the spatial layout of the city.

Classification complications:

Clouds in the northwestern part of the scene complicated the classification. Making two signature sets was attempted – one for the cloudy features and one for features in the clear part of the scene – but the two classifications did not combine when put together. Classifications in the cloudy area did not match or fit together well with connecting areas in the clear scene.

The time of the year affected the barren classification. This image was obtained in March, the dry season in Mexico City. A scene from the rainy season probably would have resulted in lowered temperature values because a significant portion of the barren land would be flooded. It would be interesting to examine the land classification in terms of wet and dry seasonal variation relative to surface temperature. Evaluating temperature at a different time of the day or night will likely not change the results as the barren land area experiences a daily temperature range similar to the other urban land uses.

These results are consistent with land use-temperature patterns found by other investigators in other cities. Improved land use classifications would shed more light on specific types of areas that are experiencing elevated temperatures.

UHI Mitigation Plan Application

As seen in the background UHI information and case studies, there are several different ways to impact UHIs. For the purposes of this hypothetical application to Mexico City, the main strategies consist of increasing the amount of green cover and changing the surface color of roads.

Increasing Green Space:

Without detailed land use data or zoning information, it is difficult to create reasonable estimates of how the amount of green space can be modified in existing land uses in Mexico City. To work in this situation of uncertainty, a scenario used in a previous paper was used as a model for increasing green space.

In a study by Douglas, Hudischewskyj and Gorsevski, the authors listed the "expected percent change in vegetation cover" for several different urban land use categories. See Table 4-2.

Table 4-2: Percent Change in Vegetation Cover by Urban Land Use Type (Douglas, et al., 2000).

Urban Land Use Category	Percent Change in Vegetation Cover
Residential	18
Commercial	18
Industrial	8
Transportation/ Communication	4
Industrial & Commercial	12
Mixed Urban/Built-up	11
Other Mixed or Built-up	11

Their vegetation cover change numbers were based on the work of the Heat Island research group at Lawrence Berkeley National Laboratory (LBNL). These numbers were based on "field measurements and laboratory studies".[60] According to the LBNL report, vegetation cover was modified assuming each building unit in a land use category would get a specific number of

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[60] Douglas, et al., 2000.

additional trees.[61] The Douglas, Hudischewskyj and Gorsevski study used these values for Washington, D.C., Baltimore, MD, Philadelphia, PA, New York, NY and Boston, MA.

To apply the vegetation cover change numbers to this study, the values had to be generalized to accommodate this study's broad land use classifications. Of the four land use categories in this study (water, urban/industrial, green space and barren land), only the urban/industrial category could be subject to a change in vegetation cover[62]. Consequently, the percent change in vegetation cover values were averaged together to get an overall percent change in vegetation cover value of 12%[63].

The urban/industrial temperature value was weighed with the green space temperature. In the Image Analysis section above, two estimations of temperature were made – one including surrounding mountains and one without. The estimate that included surrounding mountains was used for a more conservative difference between urban and green space temperature.

Weighing the urban/industrial temperature value with 12% of the green space temperature value resulted in a temperature change of 1.2°F[64]. Admittedly, this is a very rough estimation, but it is the best that can be performed with limited urban land use data.

This predicted temperature change is subject to go up or down based on a number of variables. As discussed before, the amount of cloud cover in the satellite image affects the quality of land use classification. With a finer level of urban land use information, more subtleties in the data could be discovered and could, consequently, affect temperature change.

The temperature data collection time also influenced the predicted temperature change value. The data used here was collected mid-morning, before the peak daily temperature arrived in the city. To get temperature data from another time in the day or night would require using a different satellite or acquiring data from aerial photographs. 24-hour average temperature data might offer a better reflection of temperatures in the city, but would be more difficult to acquire.

Lighter color road network:

Based on 2002 data provided by the Secretaria de Tranporte y Vialidad Desarrolló el Programa Integral de Transporte y Vialidad (SETRAVI) there were 2,601,758m^2 of primary roads that required corrective maintenance and 4,162,812 m^2 of primary roads that required preventive

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[61] Taha, et al., 2000.

[62] Barren land was not considered because it is assumed to be unsuitable for vegetation.

[63] The percent change values of all the urban land use categories were averaged together (unweighted). The result was 11.7% and was rounded up to 12%.

[64] Urban/industrial temperature – Increased vegetation urban/industrial temperature = 72.35 – 71.20 = 1.15°F.

maintenance.[65] If the roads that required corrective maintenance were rebuilt with portland cement concrete, less heat would be absorbed and retained because the albedo value would change from approximately 0.1 to 0.35. The total area of roads requiring maintenance is less than 7km^2. If the rest of the primary roads (roads in good condition) were considered, the amount of surface that could be changed would increase to more than 17km^2 of the 710 km^2 of urbanized space in the Federal District of Mexico City, or more than 2% of city surface.

This is a small physical change, but studies in Los Angeles show that several small changes together can produce a significant impact on temperature. Increasing roof albedo by 0.35 and increasing pavement albedo by 0.25 in Los Angeles resulted in a predicted 1.5°C decrease in downtown Los Angeles temperature.[66] Another study by Rosenfeld showed increasing average albedo from 0.13 to 0.26 in Los Angeles would result in a 2-4°C decrease in midday summer temperature.[67]

Similar results are expected for Mexico City. This study lacks adequate parcel level data that can be used to measure the amount of potential modifiable surface area in each land use category and to determine the average albedo value by land use category. It is therefore difficult to make the equivalent estimation of how albedo change would affect temperature in Mexico City.

Limitations to the study method and dataset:

The methodology used in this study follows the work of previous UHI researchers. Unfortunately data access limitations forced certain modifications to the original set of steps. Future work on Mexico City's UHI mitigation plans should have access to detailed urban land use GIS data to better replicate previous studies.

Access to detailed urban land use GIS data may be problematic in certain countries. To get around this, more detailed land use classification standards could be applied or aerial photography could be employed to get finer resolution information for land use categorizations.

To add another dimension to the analysis, it would be interesting to examine the influence moisture has on temperature. This analysis was done on data from the dry season in Mexico City and a significant area was classified as barren land; during the rainy season this area might be classified as another land use category. There could be wet and dry seasonal variation relative to

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[65] Zepeda, 2003.
[66] Taha, 1997.
[67] Rosenfeld, 1995.

surface temperature. This additional level of analysis would require at least two different Landsat 7 scenes – one from the dry season and one from the rainy season.

In future work each scene should be cloud-free. It is possible to obtain clear scenes, but this study was limited to no-cost data. The only free Landsat 7 scene available had clouds. The USGS makes it very easy to find zero cloud cover scenes. The USGS Global Visualization Viewer (http://glovis.usgs.gov/) website presents cloud and date information for Landsat 7 data users.

Implications

The potential temperature decrease described from increasing green space and replacing dark surfaces with lighter colored surfaces has several implications.

Improved Air Quality:

Lower temperature can directly and indirectly result in improved air quality in Mexico City. Indirectly, lower temperature can result in less electricity use required for cooling purposes. Less electricity use means less power generation, which results in lower emissions from lowered energy generation needs.

The decrease in emissions in Mexico City varies from the US cities evaluated by LBNL reports because of two factors. Factor 1: All of Mexico City's power plants are fueled by natural gas. Natural gas power generation produces less SO_2, NO_x, PM_{10} and CO_2 than the typical east or west coal burning plants in the US. Only Volatile Organic Compounds (VOCs) production is comparable to the coal burning plants. Nevertheless, VOCs are still a compound of concern since it is one of the primary causes of ozone (smog).[68] Factor 2: Mexico City residents utilize air conditioning differently than the US cities evaluated by LBNL reports. Generally, there are less air conditioners available and residents use less air conditioning because the city has mild summers.

Lower temperature can directly result in improved air quality because "the cooler temperature would lower smog."[69] In other words, higher temperatures speed up the reaction that forms ozone and consequently, smog. In Figure 4-8, ozone level is plotted against temperature based on Los Angeles data. Above 74°F, smog levels begin to exceed the National Atmospheric Air

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[68] http://www.infinitepower.org/calc_pollution.htm.

[69] Rosenfeld, 1997.

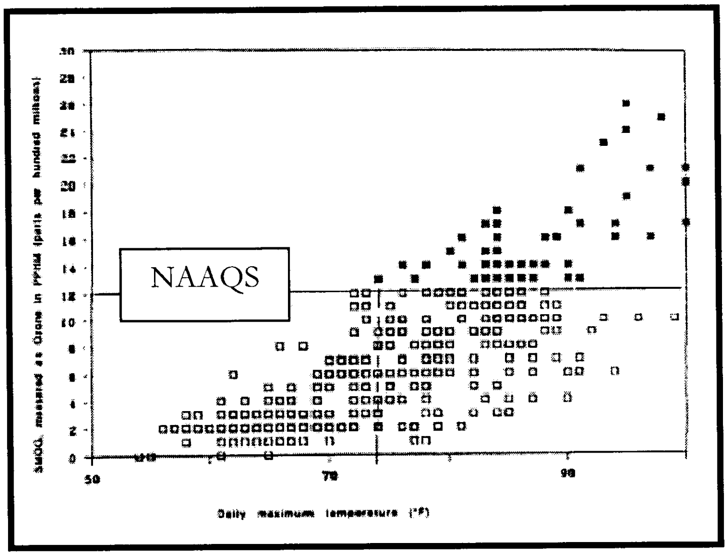

Figure 4-8: Ozone level against temperature in Los Angeles, CA (Source: Akbari, 1990).

Quality Standard (NAAQS). As the temperature increases, the ozone exceedance increases. The average high monthly temperature in Mexico City exceeds 74°F four months of the year.[70]

The increased urban greenery can also improve air quality by capturing air pollutants. Plants uptake CO_2 through photosynthesis and turn it into plant biomass. Park trees can absorb up to 85% suspended particles.[71] See Figure 4-9 for an illustration of how trees influence air quality.

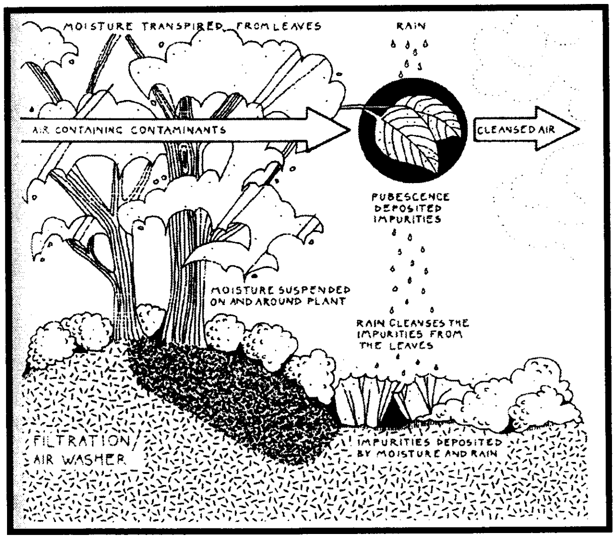

Figure 4-9: Effect of trees on air quality (Source: Johnston, 1993).

While trees uptake air pollutants and cleanse the air, the pollution problem does not stop there. The air is consequently cleaner, but the pollutants do not simply disappear. The pollutants

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[70] http://www.weather.com/outlook/travel/climatology/monthly/MXDF0132.

[71] Johnston, 1993.

remain on the leaves of trees and rain eventually washes the impurities away. These pollutants can then enter waterways and contribute to water pollution. This is an unfortunate consequence and is more evidence for the argument that environmental protection should not be subdivided by media (as is done at the US Environmental Protection Agency), but seen together as a continuum.

Urban Agriculture:

Potentially, the rooftop gardens included in this plan could be planted with productive vegetation that could be a food source for its owners. According to an Inter-American Development Bank report, the Urban Agriculture Network estimates 25-75% of all urban families in Latin America produce food in green spaces, depending on climate and culture.[72] Beyond providing food for a household, urban agriculture can be a more sustainable form of agriculture where the production and consumption of a crop are more closely linked in terms of distance and in terms of production costs.

Summary

Using satellite imagery to evaluate the land use-temperature connection in Mexico City revealed the barren land outside of Mexico City had a higher average temperature than the urban/industrial land use type inside the city. This unexpected result was attributed to time of year that the image was taken. From then, following the model established by previous UHI researchers, the effects of increasing green space and altering albedo were explored. The potential temperature decrease from increasing green space was estimated to be about 1°F. A final number for altering albedo was not determined because the detailed land use data required to make such an estimate was unavailable.

Implications for this estimated decrease in air temperature include improved air quality. Indirectly, lower temperature can result in less electricity use required for cooling purposes; directly, lower temperatures slow down the formation of ozone. In addition, with the added green space, there is more potential urban agriculture.

The main limitation to the study method was the lack of detailed urban land use data. In future studies, better land use data through finer resolution aerial photography or parcel-level GIS data will allow for a better quantification of what UHI mitigation measures can make on surface temperature.

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[72] Sorenson, 1997.

Chapter Five: Status of Mexico City UHI Plans and Requirements of Future Implementation

Status of Mexico City UHI Plans

At this point, Mexico City has no official UHI mitigation plan at a level comparable to the programs of Singapore or Tokyo. An informal sample of city officials at a range of levels of government office were generally familiar with the underlying concepts of the UHI effect and how the phenomenon could contribute to the air quality situation in the city. This sample was biased, as most of the people approached were already oriented towards an environmentally-aware approach to city planning and management.

Nevertheless, from initial conversations, there is openness to thinking about the UHI framework as a method to improve air quality. As stated before, there is not an explicit UHI mitigation plan, but there has been interest in particular UHI mitigation strategies, specifically green roofs. The Federal District of Mexico City has invested time and financial resources into the implementation of a green roof initiative. At one point the Secretaría de Medio Ambiente Gobierno del Distrito Federal had a green roofs initiative program. This program has since been dissolved because of funding considerations.[73]

Now, the work of examining green roofs as a potential Federal District-wide effort lies with the authority of the Unidad de Bosques Urbanos y Educación Ambiental office. Their work looks into the technical aspects of new roof growing mediums, irrigation systems and methodological issues involved with bringing a roof garden to a building. The office's final assessment of a green roof program in the Federal District is expected later this year. In the meantime, the Federal District has tax incentive programs in place for businesses to integrate roof gardens into their factories and office buildings. Businesses receive tax incentives for contributing to a "green-roof" fund. The intent is to maintain a self-sustaining fund that will be a financial resource for the green roof program. Most of the focus has been on industrial and commercial organizations and less on the residential sector.[74]

Little information was discovered regarding the federal or metropolitan area's interest with rooftop gardens.

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[73] Vasquez, 2003.

[74] Castro, 2003.

Implementation Plans

Implementing an UHI mitigation plan in Mexico City involves many different factors being in place and available to respond to political, social and economic interests. It is beyond the scope of this study to address all of those areas. Rather than address each of those topics, a survey of environmental planning issues that would likely appear in applying an UHI mitigation plan to Mexico City is presented.

Urban Forestry

Urban trees are a crucial piece in creating an UHI mitigation plan that will improve air quality. Integrating, maintaining and preserving trees must be a part of a general urban forestry approach to ensure the effectiveness of the trees. Work by the Davey Resource Group, commissioned by the United States Department of Agriculture Forest Service outlines a management program of urban trees for the purpose of improving air quality.[75] The report discusses the relationship between tree canopy cover and the air quality improvement and approaches to increasing tree canopy cover.

An effective urban tree management plan ought to include provisions for area-based tree canopy requirements. As recommended by the study by Stone and Rodgers mentioned in Chapter Two, a specific number of trees should be planted or preserved in proportion to the amount of area being developed. Placement of trees is another important consideration. According to this study, dense isolated clusters of trees are less thermally efficient than well-distributed trees.

Work by the LBNL Heat Island group, additional trees added from an urban forestry program will not require additional irrigation beyond normal rainfall. This conclusion came from work they did in Los Angeles. They found that the water requirement for the growth of the newly planted and preserved trees could be supported from normal rainfall, except for the initial few years.[76]

Finally, it is vital to consider only trees that are classified as low VOCs emitters. Otherwise, the preserved or newly planted trees will actually add to the problem by producing excessive amounts of VOCs that can react and form smog.

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[75] Luley and Bond, 2002.
[76] Rosenfeld, 1997.

"Cooling credits"

The LBNL Heat Island Group puts forward extending a "cooling credits" program to roofing, pavement and landscape contractors to encourage the use of the UHI mitigation strategies. This type of program, like emissions trading, aims to improve air quality. A cooling credit program would give an additional incentive for incorporating UHI mitigation measures in new construction and renovations that would help lower temperature and therefore slow the formation of smog. Each respective contractor association would sell cooling credits for their association members. These businesses would encourage cool surfaces to customers: roofing contractors would promote the application of cool roofs, pavement contractors would support the use of lighter pavements and parking lots and landscape contractors would promote the use of urban trees and other urban vegetation.[77]

A similar strategy could be pursued in Mexico City. Such a program would require the support of at least those governments at the municipal or state level to have the resources to bring in a critical number of construction associations involved. In addition, implementation could be more easily justified if temperature was recognized as a cause of smog on the same level of NO_x or VOCs, as is the case in the United States.

Timeframe

The number of ozone exceedance days will not drop overnight as a result of using UHI mitigation strategies to improve air quality in Mexico City. Coordination among state and local community groups, private and public interests and consumers and manufacturers ought to be in place to achieve maximum potential savings and air quality improvement. Barring that, small steps can be made that can make a dent into total potential benefit.

A first step is to make these surface changes as maintenance is required. Rather than replacing functioning roofs right away, they should be upgraded to cool roofs when they require maintenance. These surface improvements should be incorporated into the building's lifecycle. Most roofs have a lifespan around 15 to 20 years; if all roofs were upgraded at the end of their lifespan, in 15 to 20 years, maximal impact on temperature from green roofs and lighter roofs would be seen.

For new construction, integration of green building design characteristics will also contribute to temperature improvement in the city. Office buildings and hotels have a particularly important

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[77] Rosenfeld, 1997.

role in this area as they can achieve not only financial savings from energy efficient design, but they can experience increased real estate valuations for the added green space.[78] As in the case of Singapore, the implementation of the "city beautiful" concept helped increase foreign investment into the city-state.

Institutional Challenges

At this time, the Federal District has a unique opportunity to take advantage of one of their urban renewal programs. As described earlier, the Federal District is encouraging the relocation of informal settlement residents in conservation areas to the city center, where infrastructure and services already exist. The government is renovating abandoned and dilapidated buildings and making them suitable for residential use. While restoring these buildings, the government has the chance to modify these structures to be more energy efficient and sustainable in the urban context. In addition, adding green roofs and more green space would provide more pleasant surroundings for the newly displaced citizens.

When this idea was posited to senior officials in Secretaría de Desarrollo Urbano y Vivienda of the Federal District[79], there was agreement this would be the most judicious way to renovate city core buildings. Unfortunately, these UHI mitigation strategies are seen as too costly. Getting to the point where these urban renewal programs are acknowledged has been a difficult job and adding urban greenery is seen more as a luxury than a necessity.

Cost was another issue cited in another municipal office. Several years ago, the Secretaría de Medio Ambiente of the Federal District had an office devoted to green roofs. The office was dissolved because of funding considerations. Mexico City must move from a position where UHI mitigation strategies are seen as luxuries to where they are seen as part of the necessary urban infrastructure. Increased public and building contractor awareness along with coordinated effort amongst municipal agencies can increase level of effort expended to bring more UHI mitigation strategies into practice. As these strategies become more integrated into building and infrastructure lifecycles, the market for these solutions will grow and costs will go down. The investment in UHI mitigation reaches beyond urban beautification and leads to improvement in air quality and consequently human health.

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[78] Akbari, 2001.

[79] Atrian, 2003.

Conclusion

The increasing urbanization that Mexico City faces will strain the city financially, ecologically and politically. The growing influx of rural dwellers moving to the city will create demand for more services and infrastructure, drive real estate development and add to the number of constituents politicians serve. The expanding city phenomenon cannot be ignored.

With the intention of expanding the strategies used to reduce air pollution in Mexico City, this study presented the case of Urban Heat Island (UHI) mitigation. The first section of this study sought to link urbanization, land use and air quality so as to bring the air pollution problem out of the strictly ecological context and into the larger field of urban planning. The concept of the UHI effect was introduced and the nexus of temperature, air quality and land use was described. Driving factors of the UHI, previous research on UHI mitigation and UHI mitigation strategies were explained. Cases studies of Tokyo and Singapore were explored through the cities' justification of their UHI plan and their methods to keep the public interested in this topic.

The last part of this study focused on analysis and recommendations for applying UHI mitigation to Mexico City. A potential UHI mitigation scenario in Mexico City was described and the benefits of increasing green space and altering albedo were estimated. These surfaces changes were based on a model established by previous UHI researchers. The potential temperature decrease from increasing green space was estimated to be about 1°F. In future studies, better land use data from high resolution aerial photography or parcel-level GIS data will allow for an improved quantification of what UHI mitigation measures can make on surface temperature.

The study concluded with an examination of current UHI work in Mexico City. Considerations for planning a UHI mitigation strategy for Mexico City were suggested including an urban forestry management program and introducing "cooling credits" to encourage energy efficient urban design.

Mexico City clearly faces challenges to maintain a viable UHI program. With strained budgets, balancing the social, economic, political and environmental health of residents in a cost-effective and holistic way becomes even more important. The city must counter the trend to build out into the undeveloped regions and encourage new, sustainable growth in the abandoned city centers. This involves overcoming a significant institutional challenge as the benefits and costs affect different parties. In addition, UHI mitigation is an investment for the future and unless there is substantial public interest, it is difficult to justify the costs of a program that will not receive benefits until sometime in the future.

Fortunately, these challenges can be overcome. As seen in Tokyo and Singapore, there are many different actors working together to implement effective UHI mitigation strategies. Mexico City can follow this model of coordinated agency activity and public education programs. With added public involvement, UHI mitigation can be framed as more of a required infrastructure investment, like roads, rather than a luxury aesthetic activity. This framework brings together seemingly unconnected activities like urbanization and air quality to help create a more sustainable city where urban design, energy efficiency and awareness of ecological principles are all brought together in the planning of a city.

Appendix A: Abbreviated list of air pollution reduction measures

Cars:

- Retrofit private vehicles with catalytic converters
- Phase out of leaded gasoline
- Tightening gasoline vehicle emission standards

Public Transportation

- Replace gasoline microbuses with new gasoline or diesel buses.
- Expand the Metro
- Create a suburban train system

Infrastructure

- Construct rings and metropolitan corridors
- Industrial emissions controls (on HCs, NO_X, and PM_{10})
- Low-NO_X burners in local power plants

Environmental

- Reforestation in rural and urban areas
- Environmental information outreach.

Source: Molina, 2002

Appendix B: Low Biogenic Emission Trees

Family **Genus species 'cultivar'**	**COMMON NAME**
Rosaceae Amelanchier alnifolia	MOUNTAIN SERVICEBERRY
Ericaceae Arbutus menziesii	MADRONE
Ericaceae Arbutus unedo	STRAWBERRY MADRONE
Cupressaceae Calocedrus decurrens	INCENSE CEDAR
Pinaceae Cedrus atlantica	ATLAS CEDAR
Pinaceae Cedrus deodara	DEODAR CEDAR
Ulmaceae Celtis sinensis	CHINESE HACKBERRY
Fabaceae Cercis canadensis	EASTERN REDBUD
Fabaceae Cercis occidentalis	WESTERN REDBUD
Cupressaceae Chamaecyparis nootkatensis	NOOTKA CYPRESS
Cupressaceae Cupressocyparis leylandii	CUPRESSOCYPARIS
Cupressaceae Cupressus glabra	SMOOTH ARIZONA CYPRESS
Cupressaceae Cupressus macrocarpa	MONTEREY CYPRESS
Cupressaceae Cupressus sempervirens	ITALIAN CYPRESS
Rosaceae Eriobotrya japonica	LOQUAT
Oleaceae Fraxinus pennsylvanica	GREEN ASH, RED ASH
Oleaceae Fraxinus velutina	ARIZONA ASH
Aquifoliaceae Ilex aquifolium	ENGLISH HOLLY: MANY VARIETIES

Aquifoliaceae Ilex cassine	DAHOON HOLLY
Lythraceae Lagerstroemia indica	CRAPE MYRTLE
Lauraceae Laurus nobilis	GRECIAN LAUREL, SWEET BAY
Oleaceae Ligustrum lucidum	GLOSSY PRIVET
Oleaceae Osmanthus fragrans	SWEET OLIVE
Rosaceae Photinia fraseri	FRASER PHOTINIA
Pinaceae Pinus halepensis	ALEPPO PINE
Pinaceae Pinus sabiniana	DIGGER PINE
Cupressaceae Platycladus orientalis	ORIENTAL ARBORVITAE
Podocarpaceae Podocarpus macrophyllus	YEW PINE
Rosaceae Prunus armeniaca	APRICOT
Rosaceae Prunus avium	SWEET CHERRY
Rosaceae Prunus caroliniana	CAROLINA LAUREL CHERRY
Rosaceae Prunus lusitanica	PORTUGAL LAUREL
Rosaceae Prunus serotina	BLACK CHERRY
Rosaceae Pyrus calleryana 'aristocrat'	ARISTOCRAT FLOWERING PEAR
Rosaceae Pyrus calleryana 'bradford'	BRADFORD PEAR
Rosaceae Pyrus kawakamii	EVERGREEN PEAR
Anacardiaceae Rhus lancea	AFRICAN SUMAC
Caprifoliaceae Sambucus mexicana	HAIRY BLUE ELDERBERRY
Lauraceae	

Sassafras albidum	SASSAFRAS
Ulmaceae	
Ulmus americana	AMERICAN ELM
Ulmaceae	
Ulmus parvifolia	CHINESE ELM, CHINESE EVERGREEN ELM
Caprifoliaceae	
Viburnum rufidulum	RUSTY BLACKHAW, SOUTHERN BACKHAW
Ulmaceae	
Zelkova serrata	SAWLEAF ZELKOVA

Source: SelecTree: A Tree Selection Guide (http://selectree.calpoly.edu)

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